Dec. 1907.

Professor W. J. Hussey.
With regards of
Wm J. Humphreys

EARTHQUAKES

PLATE I.

View of the Great Fault in the Neo Valley, Japan, Formed during the Earthquake of October 28,

EARTHQUAKES

AN INTRODUCTION TO SEISMIC GEOLOGY

BY

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ILLUSTRATED

D. APPLETON AND COMPANY
NEW YORK
1907

Published November, 1907

PREFACE

PROBABLY no branch of science has made such astounding advances during the past decade as has seismology, if exception be made of the studies of radiant energy. Attention is drawn to this growth in the name "New Seismology," which refers to the fact that earthquakes may now be studied from a distant station as well as upon the ground. This term tells, however, but a part of the story; for the methods of study used in the field are being almost as thoroughly transformed as have the distinctly instrumental and physical studies made at fixed observing stations.

We have, thus, to-day two wholly different types of earthquake investigators. On the one hand, there is the body of watchmen posted at observatories, who, with the aid of delicate and largely automatic instruments, are able to announce the arrival of earth shocks and study the registration of wave motions which have originated in jars anywhere upon or near the surface of the globe. In coöperation they are now able to fix the location of the disturbed districts, and thus for the first time it is possible to issue an annual earthquake catalogue for the planet regarded as a whole. These earthquake watchmen have been trained as physicists, and are in many, probably in most, cases without special knowledge of geology. A different

body of investigators are those geologists who are awakened to appreciate the fact that earthquakes are but manifestations of the forces which are active within the earth's crust, and constitute, therefore, a most important province within their field of study.

Until quite recently the theories of earthquakes which have obtained general acceptance required the study of the subject to consist largely of mathematical computations based upon extensive compilations of data of variable and often indeterminate values. It is for this reason that the subject has been so generally neglected by geologists—a neglect reflected with sufficient clearness by the brief treatment of the subject even in the more extended manuals of geology. In the new movement for earthquake study America has as yet had little part. The disaster in California on April 18, 1906, has, however, aroused a lively interest in the subject throughout the country, and it is quite likely that seismology will soon be dignified by separate treatment in the courses of study of some of our higher institutions of learning. Plans are also being made to establish earthquake stations in connection with a number of American universities.

If the best results are to be obtained, it is essential that the physicist and his brother, the geologist, should be brought into a closer association than has yet characterized the recent study of earthquakes. The establishment of earthquake stations at universities where seismology is taught as a part of geology may be expected to do much to this end.

Essential facts concerning earthquakes have too often been overlooked because the subject has been studied less in original contributions than in text-book descriptions, which have in turn

been copied from other and earlier texts. More than in most fields of science the original monographs are intelligible to the general reader, and hence fairly full descriptions from original sources of some of the more instructive earthquakes have been included in the following pages. For the student these descriptions are not, however, meant to take the place of the original articles themselves, to which reference is made, and which should, if possible, be made directly accessible.

In preparing the manuscript of this book the author has been placed under special obligation to Mr. W. D. Johnson of the United States Geological Survey, whose extremely valuable maps of the earthquake faults in the Owen's Valley are here for the first time published. Professor F. W. Kelsey, head of the Latin Department in the University of Michigan, has rendered invaluable assistance in the treatment of the earthquake theories of the Greek philosophers. Dr. T. H. Holland, Director of the Geological Survey of India, has kindly supplied some interesting original photographs taken after the Indian earthquake of 1897. To the other gentlemen who have assisted the author by the contribution of photographs acknowledgment has been made in the text.

WILLIAM HERBERT HOBBS.

UNIVERSITY OF MICHIGAN,
August 5, 1907.

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EARTHQUAKES

CHAPTER I

THE EVOLUTION OF EARTHQUAKE THEORY

The terra firma an illusion.

ALEXANDER VON HUMBOLDT, the scientific traveler, has described for us the amazement and the utter bewilderment by which one is overcome when he experiences his first earthquake. "From earliest childhood," he says, "we have been impressed by the contrast between the ever-moving particles of water and the immobility of the firm and solid ground beneath our feet." One instant shatters the illusion of an entire lifetime, and after our rude awakening we no longer trust even the ground upon which we stand.

The first indication of a heavy earthquake is usually a low roar like distant thunder, which seems to proceed out of the earth beneath the feet. With no other warning, and this lasting but a second or two at the most, the ground swells into a low ridge which travels along the surface like a wave upon the sea. Unable to keep their feet, men and beasts alike lie prostrate upon the ground and are seized with nausea akin to seasickness. If the eyes are turned upward toward the sky the clouds seem to be arrested in their courses across the heavens. To the rumbling of the earthquake there is quickly added in cities the crash of falling masonry, and to this succeeds an uncanny gray

darkness as the air becomes filled with the dust from broken bricks, mortar, and plaster.

In places the ground opens and swallows the objects which lie upon it. Ponds are here sucked down and disappear, and great fountains of water or of mixed water and sand elsewhere gush from open fissures, so that the country is quickly flooded; but often the flow is suddenly arrested and quickly succeeded by a sucking down of the water which was so recently poured out. In places disagreeable and unsanitary odors are freed from decaying organic matter within the soil, and these fill the air with an intolerable stench. In the fraction of a minute all the destruction has been wrought, and as the gray curtain of dust slowly lifts and reveals the once prosperous city, there is disclosed a scene of desolation and misery which beggars description. Fortunate is it if to the terrors of the earthquake those of a great conflagration be not added.

Recent scenes in San Francisco.

But a few months since, the city of San Francisco was suddenly transformed, and its streets became quickly thronged by a multitude of homeless people. When the first heavy shocks had passed, nature, in the great parks, did its utmost to hide the general misery. "A clump of violets covered with a handkerchief made a pillow for a little girl burning with fever. Heliotropes, carnations, a hundred kinds of roses, verbenas, geraniums, and the glorious poppies of California, vied with each other in striving to attract attention away from the appalling scene of misery, suffering, and dismay, but in vain." On this scene an ocean wind soon blew damp and cold. "Dense fog settled down on the two hundred thousand; by midnight an almost icy rain fell upon them in this now memorable night of appalling misery."

EVOLUTION OF EARTHQUAKE THEORY

rthquakes garded as pernatural.

The cause of the sudden convulsion of Nature is, to the stricken people, involved in the deepest mystery. Unable to find a natural cause, they ascribe the disaster to a visitation of Providence. Many ancient nations were accustomed to people with their gods not only the heavens, but the earth and the subterranean regions as well. The low rumbling, the pushing up of the

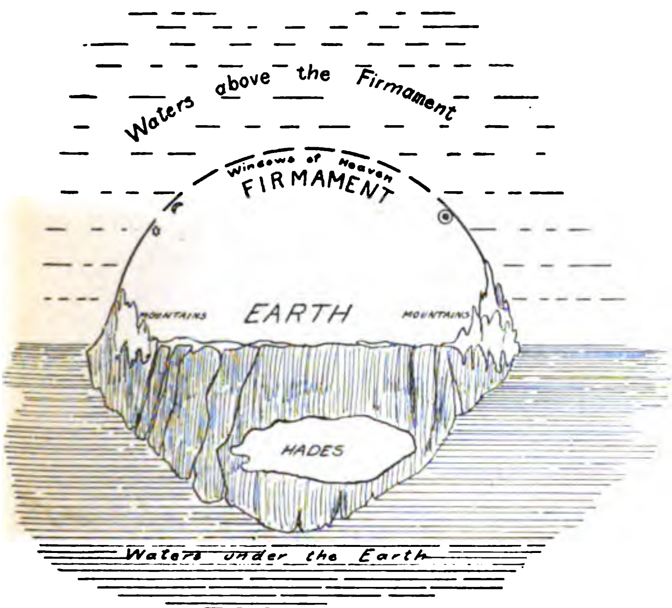

FIG. 1.—The ancient Semitic conception of the earth (after Whitehouse).

ground, the motion along its surface in a series of waves, and the visible fissures left behind—these have all confirmed them in their belief that a monster moved beneath

the ground and caused the earthquake. Some of the people dwelling about the Mediterranean had traveled to where the land ended at the borders of the sea, and the Babylonian and Hebrew conception of the earth was in consequence that of a disk floating upon the surface of water (see Fig. 1). This crude conception sufficiently explains why the Israelites had to be strictly enjoined, "Thou shalt not make unto thee any graven image, or any likeness of anything that is in heaven above, or that is in the earth beneath, or that is in the water under the earth."

Earthquakes in Holy Writ.

The lands through which the Children of Israel journeyed are among those tormented by earthquakes, and thus we find in the Scriptures a record of the destruction of cities within which not one stone was left upon another that had not been thrown down. The imagery of the poetic writings of the Old Testament reflects the scenes familiar to the Israelitish people. In the sixtieth Psalm we find, "Thou hast made the earth to tremble; thou hast broken it; heal the breaches thereof; for it shaketh." Again, in the one hundred and fourteenth Psalm, "The mountains skipped like rams, and the little hills like lambs. . . . Tremble, thou earth, at the presence of the Lord, at the presence of the God of Jacob; which turned the rock into a standing water, the flint into a fountain of waters." The supposed cause of the visitation was in most cases also expressed: "O God, . . . thou hast been displeased; O turn thyself to us again."

Poseidon, the earthquake god.

Especially in Achaia and along the western coast of Asia Minor, the sea god Poseidon was worshiped as the earthquake god. The Peloponnesus was supposed to have been his abode, the whole country was sacred to him, and in every city he was worshiped above other gods. On the coast of Achaia, where earth-

quakes were frequent and often followed by inrushing waves of the sea, there was a chain of sanctuaries erected in his honor. Once, when a Spartan army was in the field, and King Agesipolis was standing with his officers to pour a libation after the meal, the ground was suddenly shaken by an earthquake. With great presence of mind the king and his officers started a popular hymn to Poseidon, and

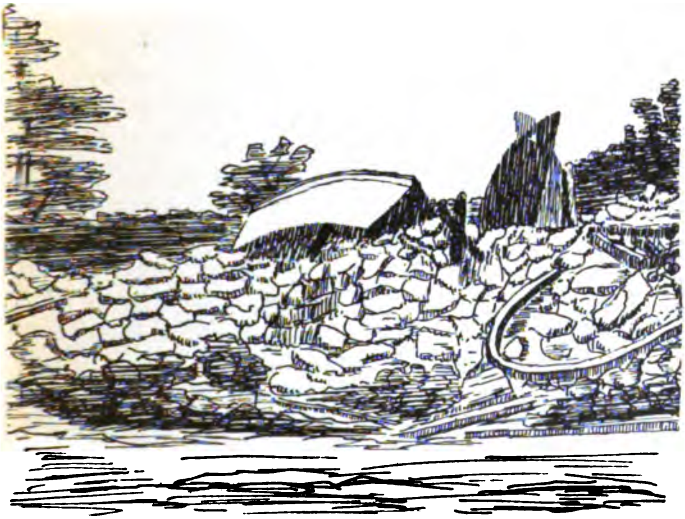

FIG. 2.—Ruins of a stone church after the Indian earthquake of June 12, 1897 (after R. D. Oldham).

the soldiers taking up the refrain, the whole army was soon singing the pæan.

Subterranean earthquake monsters of different peoples.

The form of the supposed subterranean monster, through whose movements earthquakes are brought about, has been different in the traditions of different peoples. In the early history of Japan, it was a great spider, though this in modern times has given

place to a giant catfish. In Mongolia and in the Celebes the creature has the form of a hog; in India, of a gigantic mole; in some parts of South America, of a whale; and among some of the North American Indians, of a giant tortoise.

Views of the early Greek philosophers.

In examining the theories held by the ancient Greek philosophers to account for earthquakes, it is easy to read between the lines and to see how in each case some one or more of the striking phenomena characteristic of earthquakes has been wrought into the conception. Thus Thales, who flourished between 620 and 560 B.C., holding the Semitic view that the disk of the earth was floated upon water, accounts particularly for the fact that new springs of water come into existence at the time of an earthquake. His explanation of the earthquake was that the fluctuations of the waters beneath the earth forced some of the water upward into the fissures in the disk, and that this comes through to the surface just as water enters the hold of a ship through the opening of seams in the hull.

With Anaximander, the student of Thales, it was the fissures opened in the ground during an earthquake which called especially for an explanation. His view was that in times either of drought or of protracted rains the surface of the ground cracks open, and that air from above enters in large volume and with great force. He therefore believed the chief danger periods from earthquakes to be both the dry seasons and those in which the ground has become saturated with water.

Anaximenes, who in turn was Anaximander's pupil, adopted his master's view, though he carried it a step farther in assuming that from the ground cracked by the heat or made soft by the rains, huge blocks fell in with

great impact. We have thus here the beginnings of the well-known *Einstuerz* earthquake theory which figures in the works of some German writers, and applies with special force to the curious Karst region lying to the east of the Adriatic Sea.

he various heories of Anaxagoras.

Anaxagoras, the friend of Pericles, adopted a multiple hypothesis concerning earthquakes. He apparently accepted as a possible cause the view of Anaximenes that earthquakes may arise from incaving of the earth. The cause of the dislodgment of earth blocks he believed to be in such cases the currents and tides in the waters beneath the earth. In other cases he conceived the earthquake to be brought about through internal fires which burned out the interior of the mountains until the thin crust began to shake, bend, crack, and at last collapse. He was evidently impressed by the succession of earthquake shocks, and accounted for them by a rebounding of the fallen block from the bottom of the cavity before it finally came to rest.

It is extremely difficult to set forth correctly the views of the earlier of the Greek philosophers, because of their limited horizon of scientific knowledge, because their mental attitude was so different from that of modern science, and, further, because it is so often necessary to study their theories, not in their own words, but through those of their later interpreters. According to Plutarch, Ammianus Marcellinus, and Origenes, earthquakes were believed by Anaxagoras to be the result of air from above the earth which had penetrated into its depths, and finding no outlet, pressed against the earth's crust.

Aristotle has furnished us the earliest interpretations of Anaxagoras, and his statement has been summarized as follows: He distinguishes in the earth, which, be-

cause of its form, floats free upon the air, an upper inhabited half and a lower uninhabited one. On the lower side also air is found, and this has the tendency to flow upward. To this the earth, which in all its parts is equally permeable or porous, offers as a rule no resistance. It may happen, however, that in consequence of downpouring of rain the upper portions of the earth draw together and oppose the passage of the air; this presses then from below against the earth and shakes it. This interpretation of Anaxagoras is especially valuable in view of the relation which it bears to the view of Aristotle himself, in which is contained the kernel of the later centrum theory, a theory which, with but slight modification only, has endured to the present day.

The Aristotelian theory.

The theory of Aristotle was that all earthquakes were brought about by air or gases which were contained in subterranean cavities, and which by their struggles to escape caused the shaking of the ground. Regions in which there were many caves, such, for example, as Achaia, Eubœa, and Sicily, were, of those with which he was familiar, especially subject to earthquakes. He believed, further, that a stifling atmosphere preceded an earthquake, and for the reason that all the wind had been forced within the earth cavities. Aristotle appears to have appreciated the fact that the sound which accompanies earthquakes in most cases precedes the arrival of the first shocks. His explanation for this was that sounds are finer than air and are propagated with a greater velocity. This theory that earthquakes are caused by the expansion of gases confined in subterranean cavities, fantastic as it seems to be in some of its aspects, is the starting point of the volcanic or centrum theory of earthquakes.

Views of Strabo and Pliny.

The geographer Strabo was an ardent follower of the Aristotelian earthquake theory. Great stress was laid upon the supposed fact that earthquake districts are those of many subterranean caves. Strabo tells us that the earthquakes in the valley of the Meander in Asia Minor were practically continuous. The houses rocked and their walls cracked and gaped. Most of the inhabitants of Philadelphia prudently dwelt scattered on their farms for greater safety. In view of these conditions it was a marvel, he said, that such a city should have any inhabitants at all, and a still greater marvel that it should ever have been built.

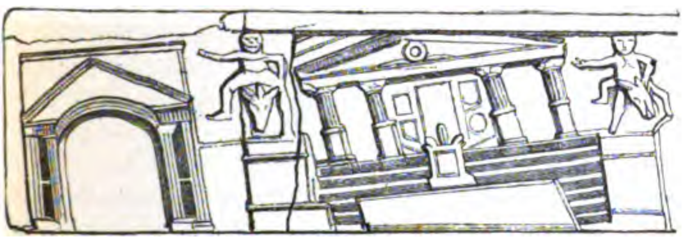

FIG. 3.—Fall of the Temple of Jupiter, at the north end of the Forum, Pompeii, in the earthquake of the year 63 A.D. On an extension of the podium toward the front two equestrian statues and an altar are seen. From a crudely executed relief (probably votive) on an altar of the household gods in the house of *Cæcilius Jucundus*, Pompeii. (After Overbeck-Man.)

Pliny the Elder, who was familiar with the phenomena of the Pompeiian earthquake of 63 A.D., and who afterwards perished during the grand Vesuvian eruption of 79 A.D., also followed Aristotle in ascribing earthquakes to wind which had penetrated into the earth and was there confined.

Conception of earthquakes by Lucretius.

The Epicurean, Titus Lucretius Carus, who lived from 95 to 55 B.C., made an elaborate discussion of earthquakes in his *De rerum natura*, or "The Nature of Things," and we may profitably use his own language in Monro's translation: "First of all take it for granted that the earth below us as well as above is filled in all parts with windy caverns and bears within its bosom many lakes and many chasms, cliffs and craggy rocks. . . . the earth quakes above from the shock of great falling masses, when underneath time has undermined vast caverns; whole mountains indeed fall in, and in an instant from the mighty shock tremblings spread themselves far and wide from that centre.

"Sometimes, too, when an enormous mass of soil through age rolls down from the land into great and extensive pools of water, the earth rocks and sways with the undulation of the water. . . . Again when the wind, gathering itself together in the hollow places underground, bears down on one point, the earth leans over on the side to which the headlong violence of the wind presses.

"The same quaking likewise arises from this cause, when on a sudden the wind and some enormous force of air gathering either from without or within the earth have flung themselves into the hollows of the earth, and there chafe at first with much uproar among the great caverns and are carried on with a whirling motion, and when their force afterwards stirred and lashed into fury bursts abroad and at the same moment cleaves the deep earth and opens up a great yawning chasm."

The fundamental idea foreshadowed in Anaxagoras and more concisely expressed by Aristotle, that the direct

Earthquake theories in the Middle Ages.

cause of earthquakes is the expansive power of confined gases within the crust, we meet again with the revival of learning which took place at the close of the Middle Ages.

Conrad of Megenburg, in his "Book of Nature," which was published in 1359, says: "Now earthquakes originate in this manner, that within subterranean cavities, and especially in the interior recesses of mountains, vapors are compacted together in such vast quantities, and under such tremendous pressure, as to exceed at times all means for restraining them. They crowd in all directions against the walls of the interior caverns, fly from one to another of them, and continue to augment in volume until they have surcharged an entire mountain. The increase of these vapors is occasioned by the stars, especially by Mars and Jupiter. When now the vapors are confined for a long period within the subterranean cavities, their pressure becomes so prodigious that they burst forth with enormous violence and rend mountains asunder. Even when they fail to break completely through the crust, they are yet able to produce a severe shock."

Essentially the same idea was reflected by Shakespeare some two and a half centuries later. When, in "Henry IV.," Glendower boasts that the heavens were on fire and the earth was shaken at his birth, Hotspur is made to say:

> O, then the earth shook to see the heavens on fire,
> And not in fear of your nativity.
> Diseasèd nature oftentimes breaks forth
> In strange eruptions; oft the teeming earth
> Is with a kind of colic pinch'd and vex'd
> By the imprisoning of unruly wind

Within her womb; which, for enlargement striving,
Shakes the old beldam earth, and topples down
Steeples and moss-grown towers.

The church and earthquake theory. The dominance of the church during the Middle Ages is strongly reflected in the new importance of the supernatural in earthquake theory. As before in Old Testament history, it was urged that God was visiting punishment upon His creatures for disobedience to His laws. To this idea Van Helmont, in 1682, gave a pseudo-scientific form by his claim that an avenging angel struck the air so as to give rise to a musical tone, and that the vibrations were communicated to the earth in a series of earthquake shocks.

The Swiss geologist, Scheuchzer, is likely to be longest remembered because, under the spur of the church's dictation, he described a gigantic fossil salamander as one of the sinners who had perished in the scriptural deluge. His good reasoning powers are, notwithstanding this stupendous error, indicated in a new theory of earthquakes which he introduced, and one which undoubtedly assigns a true cause for many small earthquakes—the shock from landslips within mountain districts. It is, however, necessary to point out that not only do landslips give rise to earthquakes, but *vice versa*, landslips are generally a direct result of earthquakes; and inasmuch as the quakes resulting from landslips are always small and local, the landslips are far more important as consequences of great earthquakes than as causes of small ones.

Support of the volcanic theory by Von Humboldt and Von Buch. The Aristotelian volcanic theory of earthquakes, though attacked by Van Helmont and his followers through their appeal to the supernatural, still held its own, and we find Volger in 1855 voicing the slogan, "Comets point to battles as do earthquakes to volcanoes."

EVOLUTION OF EARTHQUAKE THEORY

Science, like dress, has its fashions, and the changes in the one are almost as sudden and radical as in the other. Many a time has a theory become old and given place to a newer sensation, only to be later rehabilitated after its earlier service has been forgotten. Comparatively few scientific theories have attained to general acceptance which have not owed their dominance over others to some accident of birth or to the relation which they chance to bear to some related scientific idea at the moment in the ascendant.

During the last half of the eighteenth and the first half of the nineteenth century, the knowledge of volcanoes was greatly extended through the travels and the scientific labors of two German geologists, Alexander von Humboldt and Leopold von Buch. Both these men had on several occasions the opportunity to note that light earthquakes went before great volcanic outbursts, and they were entirely correct in drawing the conclusion that such manifestations generally accompany the initial stages of eruptions from volcanic vents. Von Humboldt further observed that those earthquakes which occur far from active volcanoes are much the heavier; and from this observation he was led to consider the volcano as a sort of safety-valve for the relief of volcanic forces, thus reviving a forgotten notion of Strabo's. This conclusion regarding the connection of earthquakes with active volcanoes to which Von Humboldt was led by consideration of the great Lisbon, Caracas, Peruvian, and Calabrian earthquakes, is largely responsible for the hopeless intermingling of earthquakes and volcanoes in the early literature of seismology.

Von Humboldt's idea that the heavier earthquakes occur generally in regions more or less remote from active volcanoes is, as we shall see, in harmony with the results of

modern statistical studies; but his stupendous error was in supposing that because the light shocks are connected with volcanic action, the heavier and distant ones must also necessarily be so. Earthquakes are essentially earth jars, and these may arise from a mine explosion, from a block falling in the Niagara cataract, or from the passage of a railway train. A careless and unconscious blunder thus added to the prestige of the theory from the support of Aristotle, Strabo, and Pliny, that also of Von Humboldt and Von Buch.

Modern earthquake study—Robert Mallet.

When for the first time earthquakes came to be exhaustively studied by essentially modern scientific methods, the view seems not to have been questioned that they were manifestations of explosive volcanic energy which in some way was pent up in focal cavities within the earth's crust. This modern scientific study of earthquakes may be said to have begun with Robert Mallet and his report upon the great Italian earthquake of 1857. Mallet was a man of talent, on whom honors were showered for some unusual achievements. Educated as a civil engineer, he managed with great success the foundry business of his father in Dublin. In the emergencies of the Crimean War he constructed great mortars upon new lines, and also carried out investigations which dealt with the effect of high explosives upon the life of guns.

The great Italian earthquake of 1857.

The Italian earthquake of 1857 occurred just as Mallet had completed his studies of the effects of high explosives, and he easily obtained from the Royal Society a subsidy for pursuing investigations in Italy. The results of this study he published in two bulky volumes under the title, "The Great Neapolitan Earthquake of 1857." Naples, it should be noted, was not included within the area heavily shaken by the earthquake,

which was from seventy to one hundred miles distant in the province of Basilicata. The supposed connection of the shocks with explosions inside a focal cavity was, however, so firmly fixed in the mind of Mallet, that in his report of more than eight hundred pages he did not consider it necessary to so much as raise the question, but devoted all his energies to methods for determining the depth of the supposed cavity.

le Aristote- in theory in new dress.

In giving to Aristotle's theory of earthquakes a scientific form, Mallet found it necessary to introduce a number of terms which are now commonly used in earthquake study. The meaning of each of these will be clear upon examination of Fig. 4. The focal cavity

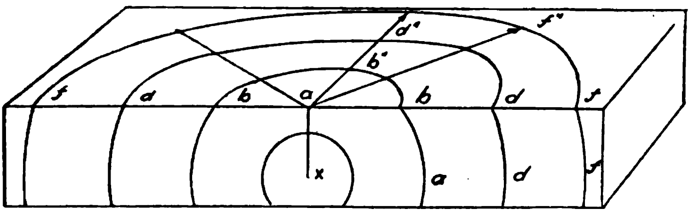

FIG. 4.—Diagram to illustrate the centrum theory of Mallet. x, focal cavity, focus, or centrum; a, epicentrum or epicenter; xa, seismic vertical; $bb''b$, first isoseismal line enclosing meizoseismal area; $dd''d$ and $ff''f$, second and third isoseismal lines respectively.

has now become the focus or centrum; the vertical line which connects it with the surface of the earth is the *seismic vertical*; the point of emergence of the seismic vertical, or the projection of the centrum upon the surface, is the *epicentrum,* now more frequently called the *epicenter.* The epicenter is located near the center of the area within which there is greatest damage to structures, and this area Mallet called the *meizoseismal area.* The more or less cir-

cular or elliptical line which he drew to bound the meizoseismal area he called the *first isoseismal line,* and this he supposed to represent the locus of those points which were all shaken with the same intensity. Concentric lines representing equal but lesser intensity of shocks and located at increasing distances from the epicenter, Mallet designated the second, third, fourth, and succeeding *isoseismal lines.*

The angle of emergence of shocks.

The method which Mallet devised in order to fix the depth of the focal cavity was based upon the nature of the damage sustained by buildings within the affected district. Having regard for the influence of window and door openings to control the cracks opened in house walls, it was assumed that the earthquake shocks had a longitudinal vibration which caused an alternate tension and compression of structures along the direction of propagation of the shocks. Since the resistance of buildings to compressive stresses or to forces tending to crush them, is much in excess of that which opposes the stresses which would pull them apart, the fissures should open in planes perpendicular to the direction of shock propagation.

To fix the direction of the destructive shocks at any given point of the shaken district, it was necessary, therefore, to observe *at the corner of a building* the direction of the plane parallel to which the principal fissures have opened, and to this plane to erect a perpendicular. If it be granted that all shocks have proceeded from a focal cavity, this perpendicular extended downward should pass into the focus or centrum. The simple principle involved in this method is set forth in Fig. 5, and a damaged building suited to its application in Fig. 6. Where no buildings suited to his purpose were to be found, Mallet sought to

fix the direction and the angle of emergence of the shocks from the position of bodies which had been thrown from positions of rest.

Inasmuch as the buildings chosen to secure the data are, in the application of Mallet's method, selected from many in their vicinity, a large element of chance obviously enters the problem, and this is augmented by the study of ob-

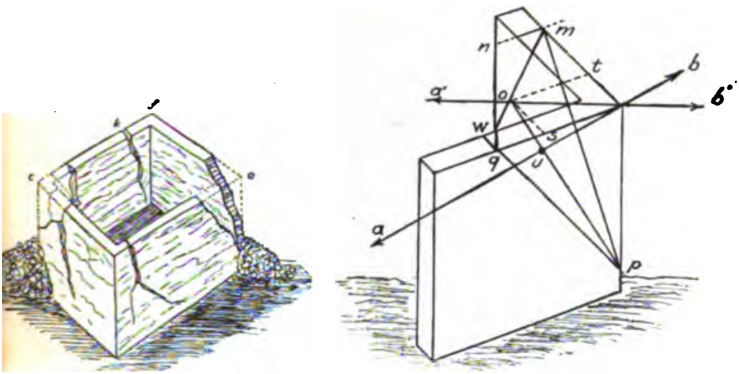

FIG. 5.—Diagram to illustrate the method of determining the position of the centrum from observation of the damage to structures. *a b*, line of emergence; *a' b'*, azimuth of shock line (after Mallet).

jects projected by the shocks, since these have undoubtedly, in many cases at least, been shifted from their positions since their fall to the ground. The data secured by Mallet were considered, however, quite assuring; for of 177 determinations made in seventy-eight villages of the disturbed district, the azimuths, or horizontal components of the shock directions, appeared to point to a definite area. The azimuths from sixteen villages passed within a circle about one-half mile in diameter, and those from thirty-two additional villages, or in all more than half the entire

number, inside a circle about three miles in diameter. It is worthy of note, however, that the intersections of emergence lines upon the seismic vertical ranged in Mallet's determinations with a noteworthy uniformity from depths of ten thousand to forty-five thousand feet, and hence

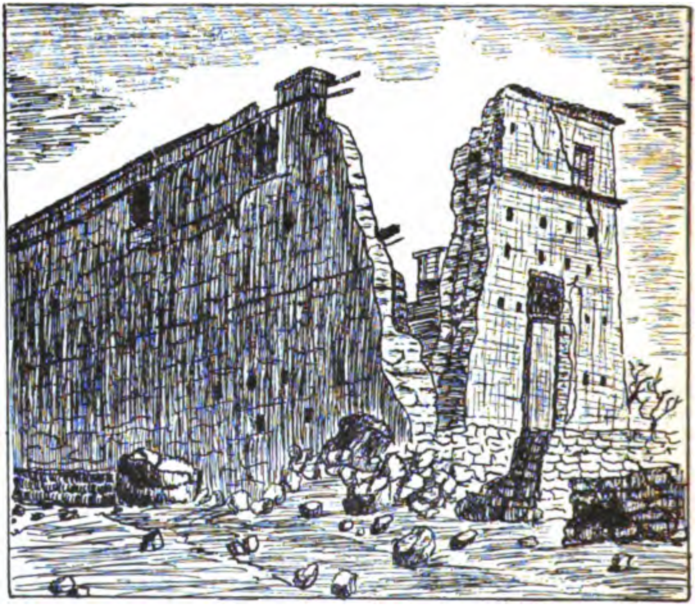

FIG. 6.—The Cathedral of Paterno in the Basilica damaged by the earthquake of 1857 (after Mallet).

refute the notion of any focal cavity whatever, as will be clear from Fig. 7. These data were, however, averaged by Mallet, who stated, "The probable vertical depth of the focal cavity itself does not exceed three geographical miles, or 18,225 feet, at the outside."

Followers of this method, strangely oblivious to the principles of geometry, have in some instances attempted to determine the lines of emergence of shock from fissures which were observed *on a single wall of a building.* In general it was found in the application of the method that the data failed to yield consistent results, and as a result it fell into disuse. Casariego found, in his study of

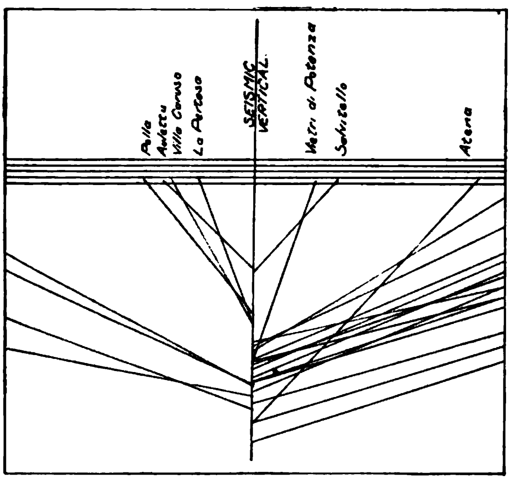

FIG. 7.—Approximate intersections of the emergence lines of shocks upon the seismic vertical as determined for the earthquake in the Basilicata in 1857 (after Mallet).

an important earthquake in the Philippines, that it was quite impossible to grade the intensity of the shocks from any point whatsoever. Professor Riccò, in his study of the Calabrian earthquake of 1894, attempted to apply the method, only to find that of observations made in thirty-three different villages, there were sixteen whose normals

pointed toward the area of greatest damage, and seventeen which pointed away from it.

The idea of coseismal lines

The loss of confidence in the accuracy of Mallet's method did not destroy the faith in the centrum theory, the life of which has been prolonged as the result of suggestions by Professor von Seebach, who, in 1872, made observation of the times of arrival of shocks at the different points within the shaken district. His assumption was not only that a centrum existed, but that shocks went out from it with equal velocities in all directions, and hence reached the earth's surface at any instant on the circumference of a circle described about the epicenter. The only irregularities from circular curvature would be such as arise from the relief of the country. A series of such circles, designated *coseismal lines,* should be concentrically arranged about the epicenter, and should thus each in turn include those points of the surface at which the shocks arrive at successive intervals of time.

This method of von Seebach, like that of Mallet, can obviously yield trustworthy results only upon the assumption that the shocks proceed from a single point. If the contrary be the fact, hopeless confusion will be the result. Further, the errors common to any timepieces other than those electrically controlled from a central station (a condition which has, perhaps, never as yet been realized in connection with a great earthquake) are such as clearly to destroy the value of the data for the purpose in view. How great these errors usually are has now been revealed by the new and "distant" method of earthquake study, which has at last afforded a reliable value for the velocity of earthquake waves, a value much in excess of that determined by von Seebach's method.

[T]he centrum [th]eory and [se]ismological [re]search.

Hypothesis points the way in research; without it science makes little progress, and discoveries result from accident rather than from design. Theories which in crude and incomplete fashion have embodied a great truth, through research have by a process of evolution discarded the false and enlarged the measure of that which is known rather than guessed. Experience shows that in almost every field of physical science there have been periods of unusual fruitfulness in discovery, and that the advance has dated from the introduction of a new point of view marking an advance over earlier conceptions. No less clear is it that where accepted theories have been essentially false the mind has been led away from observations of deep significance which held the secret behind the phenomena. Thus the progress of science has for decades, or even for centuries, been arrested.

The centrum theory of earthquakes has furnished a curious illustration of the application of this principle, for by restricting studies to a statistical compilation of data upon the one hand, and to philosophical and essentially mathematical treatment of imaginary elements dealing with the earth's interior, upon the other, earthquakes have been largely removed from direct observation, and thus in a most important field of natural science no *point d'appui* has been secured. Thus the essentially occult which is inherent in all the science of the Greek philosophers, has in a measure survived in a modern theory, and geological investigation, elsewhere so fruitful of results, because in direct touch with nature, has left its most fertile field untilled. From Mallet's time until quite recently seismology has been left largely to the care of men trained as mathematicians rather than as geologists, a condition which is reflected in geological textbooks and works of reference.

With the passing from the stage of a theory wnich, almost without opposition, has held it from the days of Aristotle, the present generation is witnessing a revival of interest in seismology on the part of geologists all over the world, but at the moment nowhere more than in America. The discovery that what is perhaps the most productive field of dynamical geology has remained so long untilled, is now attracting a throng of earnest students eager to retrieve the record of the past.

Eduard Suess and the Austrian school of seismologists.

The year 1872 is an important date in the history of seismology. On the 6th of March of that year occurred the Central German Earthquake, in the study of which Professor von Seebach developed his idea of coseismal lines, and thus gave a new lease of life to the centrum theory. In the same year appeared a paper by the great Viennese geologist, Professor Suess,

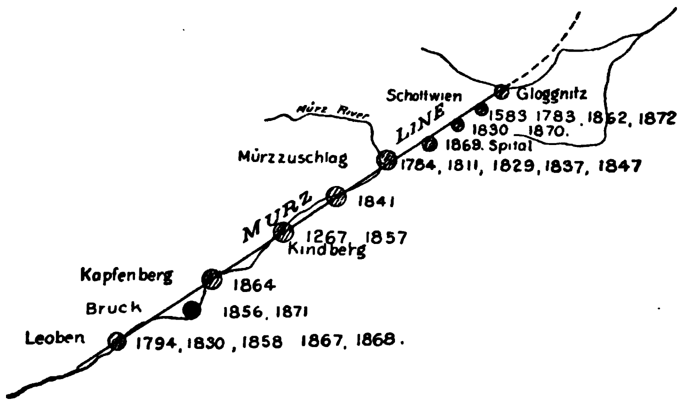

FIG. 8.—The Mürz line of habitual epicenters in the vicinity of Vienna (after Suess).

which revealed a principle strongly opposed to the centrum conception. Professor Suess's studies were made upon the

earthquakes of southern Italy, and demonstrated that the epicenters, or the points of heaviest shocks, for successive earthquakes had either recurred repeatedly at the same point or had migrated along a line which marked the position of a fault within the crust. Studies of the Lower Aus-

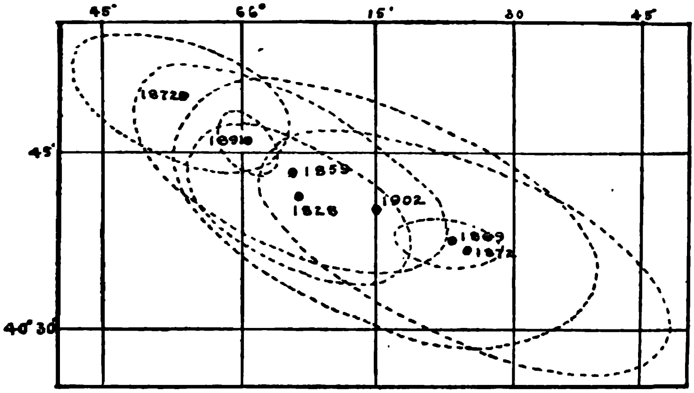

FIG. 9.—Line of epicenters near Chemakha, Turkestan (after Weber).

trian Quarter in the neighborhood of Vienna confirmed the Calabrian observations, and showed the importance of fault planes as the seats of movement and origin of the heavy shocks. Epicenters were here shown to have been habitually located at points ranged upon straight lines and proven to be the courses of geological faults. One of these "lines of shock" (*Stosslinien*), the Mürz line, is represented in Fig. 8, and a recently determined example in Fig. 9.

The Austrian classification of earthquakes. The studies of Suess above referred to have thus been the starting point of methods of study which are now associated with the school of Austrian geologists, who have been in opposition to the centrum theory generally adhered to in other countries. Their at-

tempt has been above all to place the facts of observation in connection with earthquakes *en rapport* with the geological structure of the affected district. In his great work, "The Face of the Earth," which appeared in 1885, Suess sharply distinguished *dislocation* or *fault earthquakes* from *volcanic earthquakes*; and to these classes Hoernes, his nephew and pupil, has added the type of *in-caving earthquakes* (*Einstürzbeben*) to cover especially the peculiar quakes of the Dalmatian coast.

The revival of interest in seismology.

A new epoch in the history of seismology was inaugurated when in the year 1894 Professor von Rebeur-Paschwitz detected perturbations in the movements of a delicate pendulum which he traced to earthquakes upon the other side of the planet. The possibility of studying larger earthquakes from distant points of observation was thus for the first time proven, and it at once opened a new and exceedingly attractive field for study. In the following year a Committee on Seismological Investigations was appointed by the British Association for the Advancement of Science and supplied with funds for the establishment of observing stations. In 1897 the Earthquake Commission of the Vienna Academy of Sciences came into existence. In Japan the movement for seismological research had already, in 1892, taken shape in the now famous Earthquake Investigation Committee, largely as a consequence of the terrible Japanese earthquake which in the preceding year had devastated a large territory and destroyed the lives of seven thousand people. Partly in response to a similar impulse, an American Committee on Seismology was recently appointed by the American Association for the Advancement of Science, and its initial meeting for organization was held on April 17, 1907, almost a year after

the disastrous California earthquake of 1906. At about the same time a Seismological Society of America was started upon the Pacific coast.

An International Seismological Association was founded at Strasburg in 1903, and has since published at regular intervals the "Beiträge zur Geophysik," with contributions printed in either the German, French, English, or Italian language.

The new seismology.

The term New Seismology has been applied to the science as modified by the possibilities of observation from distant stations. Thus restricted in its use, the term does not adequately call attention to all those changes which the science is now passing through. The present is in seismology a quite remarkable transitional period, and evolution is taking two distinct lines. On the one hand, geologists are fast coming to realize that an important part of their legitimate field of study is being restored to them, and bringing with it the possibility of pushing back the frontiers of the unknown through the direct application of their observational methods. This is the modern study of earthquakes *upon the ground.*

On the other hand, the new instrumental methods which have been introduced in the science, call for men skilled in the manipulation of apparatus and trained as physicists. The studies already carried out by investigators of this class are leading to far-reaching conclusions which concern the conditions obtaining in the interior of the earth. The scale of the phenomena which they are studying is essentially astronomic, and their field is the physics of the earth regarded as a whole. This is the *distant study* of earthquakes.

There is far too much danger that the two classes of workers, the geologists and the geophysicists, will pursue

divergent paths. Yet neither can do his best work alone, and the interpretation of the instrumental records in particular is rendered difficult or even impossible in the absence of some knowledge derived from close observation upon the ground.

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CHAPTER II

THE CAUSE OF EARTHQUAKES

We have seen how, at first, superstition and terror, and later traditional notions, have for centuries hemmed in the field of thought where earthquakes were concerned. With the accumulation of accurate observations a widening of this horizon has been inevitable, and we are now in a position to view the facts in their true relations, and upon them to base a theory which seems best fitted to explain them all. Seismology has too often been regarded as an almost occult science far removed from geology, whereas earthquakes are but a manifestation of the dynamics of the earth's crust. It is, therefore, to our widened knowledge of earth structure that we must look for help in seeking the cause of earthquakes.

e earth's nes of cture d flow.

One of the most valuable and pregnant of recent conceptions in geology is that which separates concentric shells of the earth's crust according to the behavior under compression of the material within them. Every inch of rock within the crust must, of course, be looked upon as bearing the burden of that column of rock material which extends upward from it to the surface. The farther within the crust be the portion of rock which we are considering, so much the greater must be the pressure upon it, a pressure which in a rough way we may compute, since rocks are upon the average a little

less than three times as heavy as their bulk of water. Thus we find that at a depth of about six miles beneath the surface this pressure must become so great that all rocks known to us would be crushed by it. If it were attempted, for example, to tunnel in rock at this depth—supposing that such an attempt even were possible—the roof of the tunnel would immediately collapse and the opening be entirely sealed up. The microscopic pores in the rock would likewise, and for the same reason, be closed.

Under such conditions the rock could never be fractured under stress, but would flow when strained in much the same manner as would a thick liquid. Should fractures be formed at the surface of the ground extending downward into the rock, they must disappear before they reach this deep stratum, which has therefore been called the *zone of flow,* or *zone of rock flowage.* The overlying zone, for equally obvious reasons, has been designated the *zone of fracture.* The contact of the two zones can never be sharp, for the reason that rocks do not all possess the same strength—are not crushed by the same pressures. They are, moreover, weaker when at higher temperatures, and the proximity of a mass of molten rock material like lava would therefore exert a marked influence in locally raising the upper surface of the zone of flow. Within an intermediate stratum, relatively quite narrow, called the *zone of fracture and flow,* rock fracture or rock flow might for any given case be determined according as the action of the forces was relatively rapid or not.

Every observer of nature in regions where the rock basement reaches the surface, knows that the outcrops of rock are cut through and through by a complex network of fissures technically known as *joints.* Where the rock strata lie nearly or quite flat, we are able to infer that

little, if any, tilting has occurred since they were first laid down. In such districts the observation is almost universal that the fissures stand nearly or quite perpendicular, and are included within a relatively small number of parallel series which mutually intersect each other, and divide the rock mass into a great number of upright prisms. Among these parallel series of the joints two are generally found which are more prominent than the others, and which intersect nearly or quite at right angles (Plate II, *A*). Now it can be shown from mathematical considerations alone that such a system of prisms as has been described is just what should result from a compression of the layers within the earth's crust, so that observation and theory are here in harmony. It is, moreover, an accepted principle in geology that the crust of the earth is constantly required to accommodate itself to a smaller and smaller nucleus, and on this account contraction keeps it in a state of compression.

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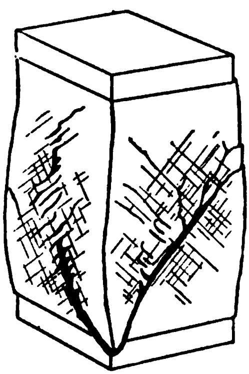


FIG. 10.—Fractures formed in a block of glass under compression (after Daubrée and Tresca).

ubrée's
periments.

While not, perhaps, in all respects, a faithful representation of the conditions which obtain within a block of the earth's crust under compression, the experiment of a distinguished French geologist, Daubrée, better than any other illustrates how the fissure network is produced. A thick block of plate glass was, in the experiments, compressed between the jaws of a testing machine until fractures appeared in rectangular sets perpendicular

to the free faces and equally inclined to the direction of the pressure (see Fig. 10).

The compression which in the earth's outer zone of fracture yields vertical prisms, must yield a result quite different within the lower zone of flow. Since the rocks in the zone of flow cannot be fractured, they accommodate themselves to the reduction of their area by being thrown into a series of folds, in much the same manner as would layers of cloth upon the bottom of a box whose sides are

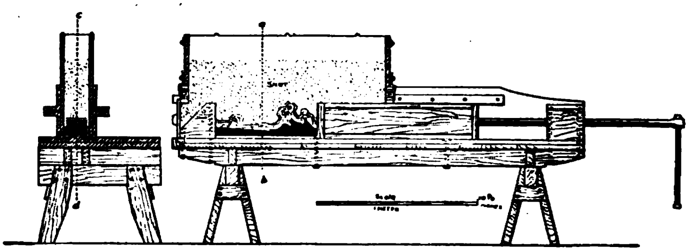


Fig. 11.—Folds produced by lateral compression of waxy layers (after Willis).

forced inward under pressure. These conditions have, however, been better reproduced in experiments by Willis through the selection of layers of waxy materials of different consistencies, and covering them in a box beneath a heavy layer of fine shot. When a side of the box is forced inward by the action of a piston the layers are thrown into folds as shown in Fig. 11.

Folds are earlier than joints within the same beds.

As we should expect, folded rocks are revealed to us at the earth's surface only when layers of overlying rocks some miles in thickness have been removed by the agents of erosion and transportation. We have become accustomed to associate complexly folded layers of this sort with rocks of the earlier geological ages,

A. INTERSECTING SERIES OF PARALLEL AND VERTICAL FISSURE (JOINT) PLANES IN ROCK EXPOSED ON THE SHORE OF CAYUGA LAKE NEAR ITHACA, NEW YORK. (After a photograph by Tarr.)

B. MODEL TO ILLUSTRATE THE ADJUSTMENTS OF BLOCKS OF THE EARTH'S CRUST BOUNDED BY FISSURE PLANES WITH FORMATION OF FAULTS.

but similar structures are no doubt being formed to-day, to be later exposed at the surface for examination by a future generation of geologists. As the surface layers are one after the other gnawed away in the course of time, rocks folded within the zone of flow are successively brought higher and higher into the zone of fracture, where subsequent compressions of the crust develop in them systems of vertical prisms in all respects similar to those produced in the earlier zones of fracture. Thus we find in all rocks exposed at the surface, whether they be folded or not, essentially the same series of vertical joints.

djust- of the by art- s.

At the time of nearly all earthquakes of the first order of magnitude, marked displacements of the ground have been observed. Generally these displacements are relatively large on a few planes only —one, two, or three—but other displacements of smaller amounts have frequently been confirmed upon hundreds of other planes. All such displacements are technically called *faults,* and when they have been definitely determined to have come into existence, or to have been extended in some way, at the time of an earthquake, they may be conveniently termed *earthquake faults.* Such faults may often be followed for a hundred miles or more as a steep wall either of earth or of rock, and are clearly due to the lifting of the land *en bloc* upon one side of the fault, the sinking of that upon the other, or to the two movements combined.

Almost as frequently a horizontal sliding of the land upon one side of the fault past that upon the other, is to be observed. A road or fence, before straight, is now found interrupted and offset and perhaps continued upon a higher terrace to which the land has been elevated (see Frontispiece). Such phenomena require for their ex-

planation that whole sections or blocks of the earth's crust be lifted bodily, that others be dropped, and that they be slid past each other in a similar manner. For the area of the entire disturbance, these individual parts of the earth's surface have undergone an adjustment by vertical and lateral movement, as might the little blocks within a mosaic, if the backing should be removed and the mosaic be slightly disturbed in its setting. Such a condition is displayed by Plate II, *B*.

Seismotectonic lines and lineaments.

The smaller earthquake faults are less frequently revealed at the surface, for the reason that the loose earth which so generally covers the rock basement is able to adjust itself to the slight change, and by compacting upon the one side of the fault and by loosening upon the other, to restrict the actual displacement to the immediate neighborhood of the rock surface. Buried planes may, however, often be traced as lines of destruction especially marked out upon the surface of the ground. Such straight lanes of special damage from earthquake have been called *seismotectonic lines*, or structure lines revealed by earthquakes. These structure lines will generally be found to be the prominent features of the country —the bases of the steep slopes of a range of hills or mountains, a straight "sag" to be followed across the country, a straight river valley, a rocky coast line, or a straight line cutting across rivers and other drainage lines, with the development of falls, rapids, or dams. These striking and significant earth features, whether definitely determined as seismotectonic lines or not, are designated *earth lineaments*, and observation shows that they are in many cases the boundaries of the earth compartments, which in the jolting adjustment of an earthquake play individual rôles (see Plate II, *B*). In the chapters which

follow we shall often have occasion to draw attention to these lines.

Lineaments, therefore, are essentially straight lines in the landscape, though often hidden beneath the gentle curves of erosion—the Hogarthian line of beauty so characteristic of mature landscapes. They are the surface expression of the fissures within the underlying rock basement, where displacement has occurred upon them. Earthquakes are thus a means of so sensitizing the earth's surface as to reveal structures which at other times are hidden beneath the mantle of rock waste. The fluorescent screen in like manner is the sensitizing agent to reveal the bony framework of our bodies beneath its fleshy covering.

Cause of the adjustment.

It is a fact well known that while some sea coasts, like Maine and Norway, have been sinking, others, like Florida, have been rising. Upon the continents mountain ranges are continuing to push up their heads, while the tireless forces of erosion and transportation are as steadily planing off the elevated areas and depositing their waste upon the seashore in the neighborhood of the land. Such changes inevitably involve a new distribution of the load upon the rocks within the zone of flow, and no argument is required to show that somewhere beneath the surface a redistribution of material by *lateral* movements must take place in order partially at least to bring about adjustment to new and ever-changing conditions. At any moment localities must exist where there is a strong tendency for the withdrawal of some of the material to supply corresponding need elsewhere. A tendency toward withdrawal of material is, at the earth's surface, a tendency toward subsidence or settlement, whereas a tendency toward elevation must exist over those districts toward which material tends to be transferred.

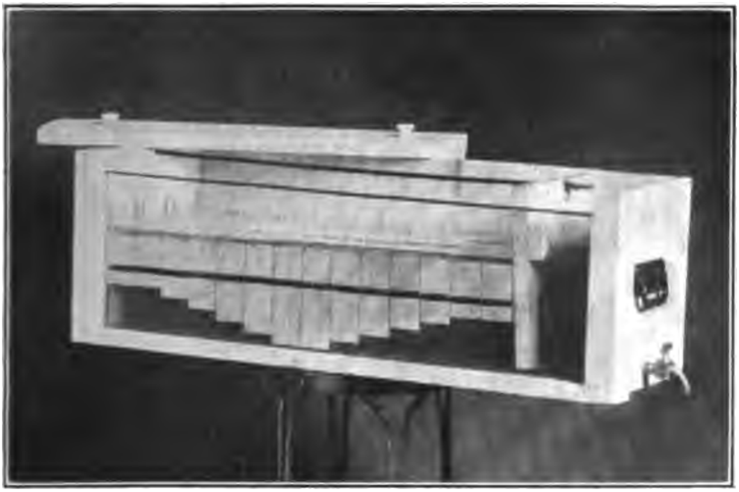
Those rocks which have been folded in the zone of flow and later exposed at the earth's surface betray little evidence of any considerable lateral transference of material such as is required to explain surface changes of level. It must follow, therefore, that these lateral transfers take place in those lower layers of the zone of flow which have seldom or never been exposed at the surface.

So long as the transfer is delayed, the downward-acting forces within the region about to be depressed are met and balanced by equal upward forces arising from the rigidity of the vertical rock prisms of the zone of fracture under the strong compression which results from earth contraction. Within the areas about to be elevated the upward-tending forces are similarly met, and the blocks are held rigidly, like wooden blocks similarly arranged between the jaws of a vise. The parallel would, however, be closer if the wooden blocks were partially supported in a bath of water.

Experiment to illustrate the cause of earthquakes.

To better illustrate these conditions, a very simple experiment may be arranged. Within a long and narrow tank, of which one side is formed of strong plate glass, is fixed near one of the ends a wooden wall fitting loosely within the tank and hinged upon its bottom (see Plate III). An iron rod, of length sufficient to project a short distance beyond the wall when in its vertical position, is fitted with screw thread and nut to serve as a vise and exert a compression upon any bodies within the tank and large enough to occupy most of its area. The tank is partially filled with water, upon which are supported rectangular prismatic wooden blocks which loosely fill the space. By varying the depth of the blocks they project when floating naturally by different amounts above the water surface. By tightening the vise they can, however, be made to take other than their natural

PLATE III.



A. Arranged to represent the blocks within the earth's crust before an adjustment has taken place.

B. After adjustment has occurred and caused earthquakes.

EXPERIMENT TO ILLUSTRATE A THEORY OF THE CAUSE OF EARTHQUAKES.

positions of flotation. If now, a board of such size as to fit loosely over the blocks in the tank be allowed to rest its weight upon them, all may be brought to the same surface level, and if the vise be sufficiently tightened, will be retained in that position after the board has been removed (see Plate III, *A*).

Tightly compressed in the vise, the bridge of blocks is held in position against forces tending to elevate it throughout those areas where blocks have greatest depth, and to sink it where block depth is least. If the compression upon the blocks be now gradually removed, a point will at last be reached when the rigidity of the bridge of blocks is insufficient to keep it in the present attitude, and adjustment will take place. This adjustment will occur when the deeper blocks are forced upward and the shallower blocks downward, and when a transfer of water goes on from beneath the latter to beneath the former. These adjustments of level among the blocks correspond to adjustments of crust blocks at the time of earthquakes and to the formation of earthquake faults about their margins. The transfer of water laterally, beneath the blocks, may similarly illustrate the transfer of material within the lower portion of the earth's zone of flow.

If, instead of allowing the adjustment to take place quietly when compression within the vise has been sufficiently reduced, we tap the swinging wall at intervals while releasing the compression, the adjustment will take place earlier. So conducted, the experiment is made to illustrate the so-called *relay earthquakes*, or the influence of shocks within one earthquake district to induce similar shocks within a neighboring one.

The water which ascends between the blocks, owing to the fact that they are not perfectly fitted to each other,

represents in the experiment the underground water which fills the fissures and the porous layers of all rock masses from very moderate depths down to the zone of flow. It is a well-known fact that at the time of earthquakes this system of underground water is suddenly deranged, and while within one portion of an earthquake district springs flow with unusual volume and bring large quantities of sand and mud with them, in other parts of the same district the water of ponds and swamps is as suddenly sucked down (see Chap. VII). The first-mentioned condition is represented in the experiment by those portions of the bridge where blocks are shallowest, and where, in consequence, they are suddenly dropped when the compression is reduced. Here the water often spurts upward with considerable force. The other condition can be illustrated by having the surface of one or more of the blocks at a lower level than the others, so that water rests upon it before the release of compression is effected.

Relation of earthquake faults to lines of no vertical stress.

There is at least one particular in which our experiment fails accurately to reproduce the conditions within the earth's crust at the time of an earthquake. We may illustrate this by looking at the subject in a somewhat different way. If in Fig. 12 the dotted lines in parallel series be supposed to represent in much simplified form a plan of the vertical joint system within the zone of fracture, it must be possible somewhere to draw a line so as to separate those regions which tend to rise from those which are tending toward subsidence. At all points, upon one side of this line, there is a force of varying intensity which acts *upward* and is met and resisted by the rigidity of the zone of fracture, regarded as a bridge or girder; whereas, on the other side of the line, there is a similar variable force which acts

downward, and similarly calls into play resistant forces existing within the bridge. At all points along the line itself there is no force acting either directly upward or

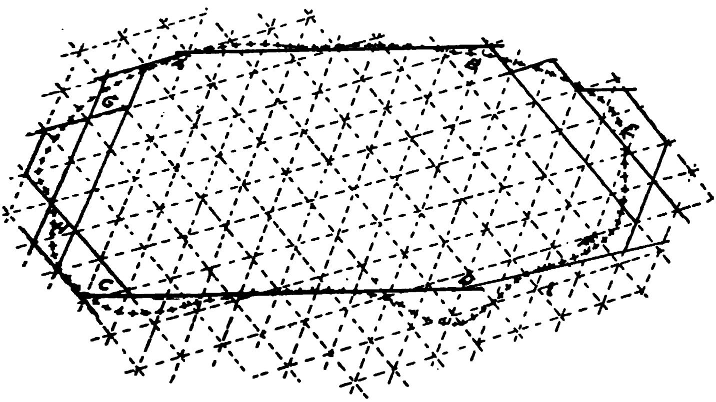


FIG. 12.—Plan of a district subject to earthquakes, and exhibiting the network of joints (much simplified), the line of no vertical stress (*ABEFDCHG*), and earthquake faults.

directly downward, and it may hence be designated the *line of no vertical stress.*

The line of no vertical stress we may think of as a line of fulcrums for an infinite number of adjacent beams which cross it at right angles, and are impelled upward upon the one side and downward upon the other. It is along this line that the crust should slip when movement finally begins, were it not for the fact that the fissures already present in the rock are planes of weakness, and make it easier for the blocks to slip upon their surfaces. Where no joints even approximately coincide with the line of no vertical stress, a slip may occur either along a series of zigzags whose elements are joint planes with *general* trend in correspondence with the line of no ver-

tical stress, or a fissure may open with displacement where no joints had before existed, as at *AB* and *CD*. To accomplish the latter, it is necessary that the stresses which tend to produce displacement should be greatly augmented, and the movement is likely to be delayed, and be of unusual violence.

Earthquake faults select a course along unhealed fissures.

It often happens that joint planes within the rocks are more or less healed, or sealed up, by the deposition of mineral matter upon their surfaces; a fact with which all are familiar from the manner of deposition of ores upon crevices. It is not unlikely that freedom of movement along joint planes, to a large extent determined by this condition, may decide whether the main adjustment within an earthquake region shall at any time occur as one or more displacements of large amplitude, or as a relatively large number of slight jars accompanying minor adjustments upon the joint system of the district. The recent catastrophic earthquake in California is an example of the first, and the frequent but slight earthquakes in New England, of the second. The great Japanese earthquake of 1891 was accompanied by the opening of a surface fault forty miles or more in length, and in places as much as eighteen feet in height (see Frontispiece), and it followed a relatively long period of immunity from earthquake disturbance. It is now a well-recognized fact that the most disastrous earthquakes of any seismic district follow the longest periods of quiet, which periods are for this reason occasions for concern rather than for complacency.

The elastic waves.

The jolting movement of the earth blocks begins suddenly and is arrested as suddenly. Such shocks are transmitted outward along the earth's surface as elastic waves, and whenever their amplitude is

large and their vibration rapid they are most destructive. These are not, however, the only vibratory movements accompanying the earthquake. Whenever two surfaces of solid bodies slide over each other, they tend to take on a more or less interrupted though progressive movement as a result of friction; and this alternation of quicker and slower motion is transmitted outward in all directions as elastic waves, whenever the moving bodies are in contact with a so-called elastic medium. The waves will be of the greater intensity, in accordance as the slips are of larger amount—have greater amplitude—and take place the more rapidly. The surface of a violin bow slips over the string of the violin, and the elastic air medium transmits the movements as waves of sound, which will be the louder the more rosin is upon the bow (greater friction), the farther it is moved over the string, and the more rapidly. The shearing motion along a fault plane produces vibrations transmitted as waves by the elastic rock material; and these waves are great in proportion as the fissure plane is formed at the time, or, if old, was before partly sealed up, and according as the movement is or is not large and rapid. Experience teaches that the slips upon earthquake faults are accomplished within a time not exceeding a very few seconds, and often measured by the fraction of a second. A definite relation seems to exist between the size of the faults produced and the extent of the damage which ensues.

Rock is a fairly elastic medium, and hence the waves which emanate from an earthquake fault are transmitted in all directions, and from each plane upon which slipping has occurred.

It is a fact of rather general observation that the greatest destruction from earthquakes, other things being

equal, is found upon the softer ground. Upon rocky ledges, except over or very near to where they have been actually displaced upon a fault plane, the damage from an earthquake is relatively small. Over so-called "made land," however, and upon alluvial plains, the maximum of destruction is to be found.

Explanation of greater shocks on softer basement.

It must be clear that the damage wrought by an earthquake is proportional to the amplitude of the shocks, or the distance through which particles of the medium are displaced by the waves. If, to exclude all conditions except those dependent upon the nature of the medium, we assume that all points at the same depth (in rock) are shaken with the same intensity, we shall see how the overlying medium itself is concerned in the problem. The same impulse imparted to solid rock, upon the one hand, and to unconsolidated material, like sand or gravel, upon the other, will be transmitted farther in the former, because of its greater elasticity; but it will produce the greatest amplitude of movement in the latter, because of its slighter cohesion. The upper layers of the soil may, on this account, be actually thrown up from the surface, together with the objects resting upon them. It is common to confuse such amplitude of distortion with elasticity, whereas it measures quite a different property. For purposes of illustration, the compact and elastic rock basement, on the one hand, and the loose soil, upon the other, may be compared to a steel wire and an "elastic" cord, respectively; and the same impulse imparted to each would be transmitted widely different distances and displace attached bodies by vastly different amounts.

Thus far we have discussed only the proximate cause of earthquakes. The ultimate cause involves a solution far more difficult to obtain. It has already been stated

ultimate se of thquakes.

that in the elevations and subsidences of the earth's surface, which are indicated in the migrations of shore lines upon the sea, we have evidence that portions of the material within the earth's zone of flow must be shifted in position laterally. It is certain that the transfer of material *upon the surface* of the earth, due to erosion and transportation, is largely a result rather than a cause of these vertical oscillations. Within delta regions, however, where rock material is deposited in largest quantity by rivers, the larger changes of level are doubtless modified in their turn by this cause.

The most helpful method of approaching the problem of the ultimate cause of earthquakes is through an examination of extended earthquake records, with a view to determine whether they betray any noteworthily unequal distribution, with a segregation within definite periods. Although excellent earthquake catalogues have been prepared for certain districts of high earthquake intensity, we have not as yet secured sufficiently full data for the earth considered as a whole. By far the best records have been preserved in Japan, and from them it appears to be true that seismic periods recur about once in thirteen years. A still more complete record applies especially to the city of Kioto, and it is claimed that these records indicate a seismic period of about six and one-fourth years, or approximately one-half the longer period noted for the records of the country as a whole.

The recent "distant" study of earthquakes, which will be described in a subsequent chapter, has now given us a fairly complete record of the greater earth quakings (*macroseisms*), extending over a number of years. Professor Milne, the veteran English seismologist, has lately announced his belief that these records indicate a definite

but shorter period of seismic maxima, corresponding to changes in direction of migration of the earth's pole (see Fig. 13). If well founded, the observation, like those made in Japan, is of very great interest, because it ascribes the migrations of rock material within the earth's

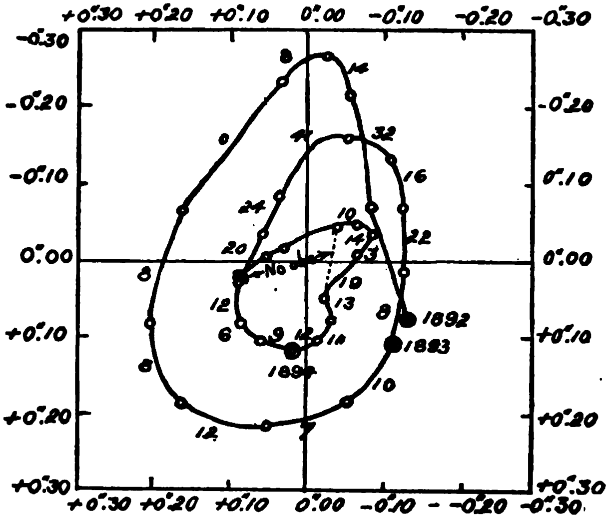


FIG. 13.—The path of the North Pole from 1892 to 1894. The divisions are tenths of a year. The numerals indicate the number of large earthquakes in each period (after Milne).

zone of flow to causes planetary in their nature. It will be interesting to learn whether the larger body of data, now sure to be accumulated in succeeding decades, will demonstrate what the present meager data dimly foreshadow.

In itself, Milne's theory is most plausible, for the migrations of the pole correspond to changes in latitude,

and these must involve migrations within the mobile portions of the earth's crust, consequent upon the distortion of the spheroid. When the direction of pole movement is reversed, sudden and temporary changes in the condition of compression within the zone of fracture (like the loosening of a vise) may precipitate an adjustment of blocks which was before impending.

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CHAPTER III

THE UNSTABLE BELTS OF THE EARTH—SEISMIC GEOGRAPHY

NOT all parts of the earth's surface stand in the same danger of earthquakes. Some portions would appear to be almost immune from earth shocks, if we may judge from historic data. The simplest way to mark out the areas which stand in greatest danger from this cause would thus seem to be to assemble the records of past earthquakes.

Earthquake catalogues.

The first to prepare a comprehensive earthquake catalogue for the globe as a whole was Alexis Perrey, a Frenchman, who devoted his lifetime to this study. He wished to find out whether earthquakes stand in any relation to changes in the moon, and while the results of his study, as generally interpreted, furnish a negative answer to his query, the investigation has none the less yielded a most important contribution to the science of seismology. Perrey's catalogue was issued in small parts which followed each other at occasional intervals between 1844 and 1871. These parts, assembled, constitute a reservoir of facts which has been drawn upon by many workers, and, notwithstanding numerous errors, has been the starting point of all later statistical work upon earthquake distribution.

A number of seismologists have addressed themselves to the preparation of more detailed catalogues for special regions—a much less difficult though still very arduous task. The countries which have the best historical data relating to earthquakes are Japan and Italy. In the first-mentioned country the records go back almost fifteen hundred years, and these have been edited by Toyama, though unfortunately the results are published in the Japanese language. From the Japanese records Professor Milne has prepared a catalogue which includes more than eight thousand shocks. The greatest of all earthquake catalogues for a single province is that of Baratta, for Italy, which has been recently issued, and covers almost one thousand pages of text. This catalogue gives with some fullness memoranda upon earthquakes as far back as the year 1000, and scattered data running back to the beginning of the Christian era. In the classical writings there exists the material for a comprehensive earthquake history of the Grecian peninsula and archipelago, which would unquestionably well repay thorough investigation.

measure instability seismicity.

Earthquake catalogues are, however, but the first step in fixing the relative degrees of instability for the different portions of the earth's surface. While some districts have in historic times never been visited by destructive earthquakes, they have very frequently been lightly shaken, while other regions, to use the picturesque European expression, have been *tormented* at frequent intervals by shocks of catastrophic violence. We have to consider, therefore, not earthquake frequency only, which is afforded by the catalogue, but earthquake intensity as well. To compare by quantitative measures, intensity and frequency must both be made to refer to definite areas. The instability of a province thus measured is called its

seismicity. Up to the present it has been possible to express the seismicity with a rough approximation only to accuracy, and the absence of complete records for many regions, and the almost total lack of any records from large expanses of territory, will tend long to maintain this condition. On the other hand, the new seismology, with its study of earthquakes from a distance, must in time remedy the defect, so far at least as the destructive shocks are concerned.

Earthquake map of J. W. Mallet.

Possessed of earthquake catalogues, their material may be made readily accessible through representation upon maps. The first important attempt in this direction was made by Professor John W. Mallet, utilizing the material of the British Association catalogue of earthquakes prepared by his brother, Professor Robert Mallet, and published with it in 1859. This map was prepared by first roughly classifying the earthquakes of the catalogue into three grades of intensity, supposed to be proportional to the figures 1, 3, and 9. For these intensities three shades of increasing depth of color were adopted upon the map. The areas which were covered by the lighter shade, for example, thus came to represent a *locus* of earthquakes which, considered collectively upon the basis of the records in the catalogue, corresponded in intensity to the lowest of the established grades. Frequency and intensity of shocks were thus mingled upon the map. Whenever the districts affected by earthquakes were not limited in the reports, the earthquakes were assumed to have shaken circular areas surrounding the points from which the reports came, and having radii proportional to the intensities adopted for the classes—that is, 1, 3, or 9. It is one of the most scientific and valuable of earthquake maps, but in comparison with later maps it suffers, owing

to the largely augmented data which have since been made available.

Professor John Milne, who in 1895 had brought out his "Catalogue of Japanese Earthquakes," prepared a map upon a wholly different basis from that of Mallet, but one ill suited to set forth his results. The Empire of Japan was first divided into quadrangles, each of which covered ten minutes of latitude and as many of longitude. (The larger scale topographic sheets issued by the United States Geographical Survey are "fifteen minute" quadrangles, and hence are somewhat larger.) Within each quadrangle of his map, Milne entered dots to indicate the number of recorded earthquake epicenters for the area. When the number of these epicenters was too large to be represented within the area of the quadrangle, the dots were allowed to extend outward beyond its limits, thus distorting the facts and reducing the value of the map.

FIG. 14.—Davison's earthquake map of Japan.

The difficulty which Milne had encountered was, however, successfully met by Davison, who by passing lines through the centers of all quadrangles which contained the same number of epicenters, secured a very lucid exposition of the facts, and an effect quite like that of the modern contour topographic map with which many high-school pupils are to-day familiar. Davison's earthquake map of Japan covers the

years from 1885 to 1892 only, but inasmuch as these years are included within the period of more careful observations in that country, the map doubtless affords a fairly correct idea of its earthquake distribution (see Fig. 14).

The seismic geography of De Montessus. It has remained for a French officer of artillery, Count de Montessus de Ballore, to devote the better part of a lifetime to the collection of material in part already assorted, though more largely dispersed, and by a process of standardization and correlation, to lay the foundations for a new branch of earthquake science—seismic geography. The vast proportions of the work undertaken by this French savant will be appreciated when it is stated that the problem that he set himself, and carried to a most successful conclusion, has been nothing less than the assembling and critical examination of all well-authenticated earthquake records, and determining by a numerical figure the relative seismicity upon a uniform scale of each earthquake district upon the globe. No fewer than 170,000 separate shocks of earthquake have thus been studied and placed in correspondence with each other.

The data utilized by De Montessus include: (1) historical records not strictly scientific, or, at least, with no scientific end in view, and hence incidental; (2) seismological records, or those made with scientific purpose, but without the aid of special instruments; and (3) seismographical observations made with the aid of delicate earthquake apparatus. The instrumental observations have in the past been subject to just criticism, for the reason that they have included the records of movements belonging in other categories. They thus err by recording in excess, whereas the seismological observations err upon the other side, through a failure to report the lighter shocks. In many regions records of the three types above given have

now been made, and in them De Montessus finds evidence that somewhat definite ratios connect the numbers of each.

assumptions of De Montessus.

In order to utilize the available data De Montessus found, in fact, that it was first necessary to establish a relation between the earthquake frequencies, as determined by his three methods, in those regions where all could be applied. It was found that

$$\text{From 44 districts } \frac{\text{seismological records (l)}}{\text{historical records (h)}} = 4.26$$

$$\text{" 28 " } \frac{\text{seismographical records (g)}}{\text{historical records (h)}} = 26.59$$

$$\text{" 22 " } \frac{\text{seismographical records (g)}}{\text{seismological records (l)}} = 6.44$$

Since these values have been determined independently of each other, it is both interesting and significant that we find a remarkable agreement when we substitute values obtained from one equation in either of the others. It is this fact which has enabled De Montessus to compare data of such varying characters.

Another basal assumption made by De Montessus was that the intensity of an earthquake is directly proportional to the area shaken; in other words, the heavier the shocks, so much larger the area over which they will be felt. This assumption is undoubtedly an outgrowth of the centrum theory of earthquakes, and can be true to a very rough approximation only. Since, however, it is to a first approximation only that we can hope to arrive from a consideration of the present scanty data, the assumption is not as serious a one, by reason of its inaccuracy, as would otherwise be the case. If earthquakes be due to movements of varying amplitude upon many either near-lying or widely scattered planes of dislocation within the earth's

crust, as the count believes, no very close relation between the area shaken and the average intensity of the earthquake is to be expected.

With this conception of the measure of instability of an

FIG. 15 *a*.—The earthquake belts and the earthquake "ovals" of the Western Hemisphere (after De Montessus and Milne).

earthquake district, De Montessus has carried out extended statistical studies for each province of the globe.

The two great-circle zones of earthquakes.

The first result of the studies of De Montessus showed that, with few and rare exceptions, the earthquake districts of the globe are included within two great belts or zones which surround it in the directions of great circles, and which meet at angles

of about sixty-seven degrees. The more important of these zones includes 53.54 per cent. of all the shocks, and is outlined by the Alps and the Mediterranean, the Caucasus, and the Himalayas. The other belt surrounds the

FIG. 15*b*.—The geosynclinals of the Western Hemisphere (after Haug and De Montessus).

Pacific Ocean, following the great Cordilleran mountain system of the Western Hemisphere, and the festoons of islands on the borders of Eastern Asia and Malaysia. This latter belt includes 41.05 per cent. of the shocks studied, so that 94.59 per cent. of all recorded shocks belong to one or the other of the two great-circle belts. The maps showing these belts are reproduced with additional data

in Figs. 15–16, the earthquake districts being represented in solid black. To bring out more clearly the relation of earthquake belts to great circles of the earth, the maps of Fig. 17 have been prepared upon a zenithal projection in which there is no distortion along those directions which go out from the pole or center of the map. The first figure thus correctly represents the circumpacific belt of earth-

FIG. 16 *a*.—The earthquake belts and the earthquake "ovals" of the Eastern Hemisphere (after De Montessus and Milne).

quakes in correspondence with the equator of the projection. The second figure likewise represents the Mediterranean-Alps-Caucasus-Himalaya great circle, here, likewise, near the equator of the projection.

sequence occurrence great rthquakes thin belts.

The year 1907 has registered a noteworthy contribution to our knowledge of seismic geology. Dr. Omori, the distinguished professor of seismology in the University of Tokyo, has brought out the fact that the world-shaking earthquakes of the past two years have occurred upon these belts in such a sequence as to indicate that the place of their occur-

Fig. 16 *b*.—The geosynclinals of the Eastern Hemisphere (after Haug and De Montessus).

rence is determined by a law, the broader outlines of which may be discerned. Upon the same belt the earthquakes do not appear in succession as an extension of the first disturbance along the belt in a sort of progression;

but relief having first been found in one province, the next disturbance is likely to occur in a distant section rather than a neighboring one. From this it seems likely that the relief from stress within the earth's crust is for the time almost complete where the earthquake occurs, and partial in its neighborhood. This fact will be apparent

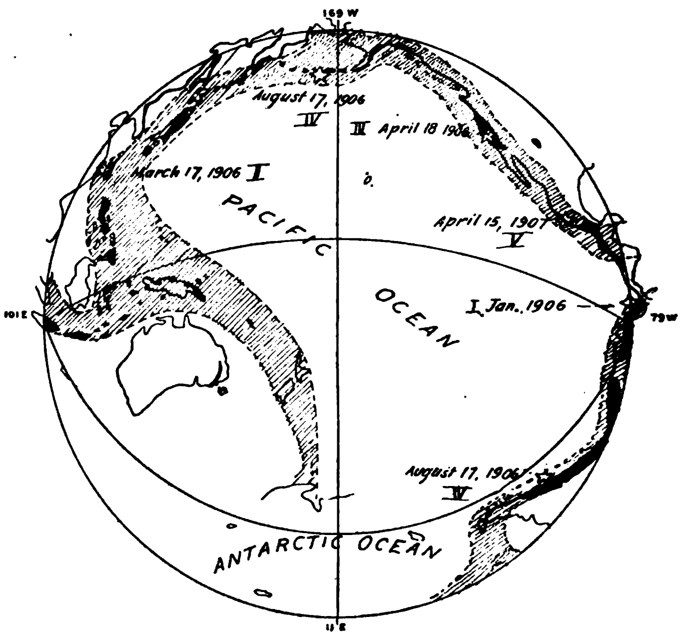

FIG. 17 *a*.—Earthquake map upon the zenithal projection to bring out the relationship of earthquake belts to great circles and the geographic positions of successive great earthquakes.

upon examination of Fig. 17 *a* and Fig. 17 *b*, upon which the facts brought out by Omori have been entered.

During Professor Omori's visit to California, after the

earthquake of April 18, 1906, he expressed the view that the next great shock upon the Pacific coast of the Americas would occur within the seismic belt to the southward of the equator. Before he had reached his distant home

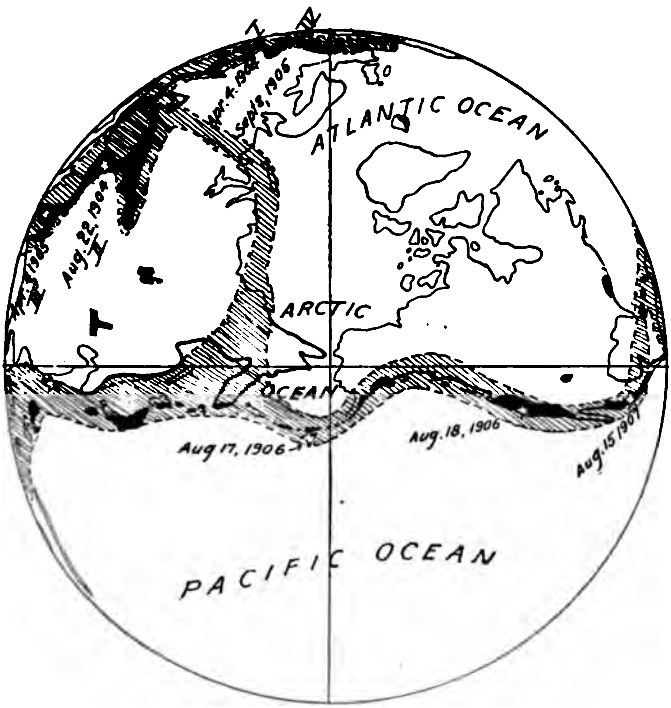

FIG. 17 *b*.—Earthquake map upon the zenithal projection to bring out the relationship to great circles.

came the shocks which were so disastrous to Valparaiso, in Chili. The earthquake in Mexico of April 15, 1907, was likewise within the same earthquake belt, and was in position intermediate between those of California and

Chili. To judge from the first reports, it was also less violent than either of its predecessors.

The relation between earthquake and volcanic districts.

It has long been recognized that the earthquake zones of the globe are also the zones of active volcanoes. This is particularly true of the circum-pacific belt of earthquakes, which corresponds accurately in position with the so-called "fire ring" or "fire girdle" of the Pacific. It is in no small measure due to this coincidence between earthquake and volcanic provinces that the dependence of earthquakes upon volcanic sources of energy has so generally been assumed. It cannot be denied that the coincidence is one of very great significance, but the relation of the one phenomenon to the other is not that which has been generally supposed.

In the clearer light of to-day we are able to say that the volcanoes and the earthquakes alike are due to the action of those earth forces which have built up the near-lying mountain ranges. To form such mountains it was necessary for great strips of the earth's crust to be pushed up in successive movements between lines of fissures. The jolting movement of the earth blocks as they have slipped over each other accounts for the earthquakes, and the melted rock material which, as a result of the movement, has been squeezed out, either along the fissures or, as is more frequently the case, at their intersections, has built up the volcanoes. Wherever mountains are still growing, earthquakes and active volcanoes are to be found. Where they have ceased to grow, there the earth does not shake—it is dead—and lava is no longer exuded through the fissures in the surface.

Ever since the Middle Ages has it been common to connect earthquakes with near-lying volcanoes. This is explained not only by the general correspondence between

earthquake districts and the belts of active volcanoes to which we have just referred, but even more to the fact that all volcanic outbursts of considerable violence are accompanied by light shocks of earthquake. It might, perhaps, be supposed that such evidence would be well-nigh conclusive, but when it is borne in mind that an earthquake is merely an earth jar, and is occasioned by the fall of a block of limestone in the Niagara cataract, by the passing of a train of cars, or by the collapse of a cave roof or of a coal mine, quite as much as by a volcanic explosion, we see that the causes of such earthquakes may be many and various.

Earthquakes in relation to eruptions in volcanoes.

It is significant that all the types of light earthquakes which have been mentioned are in degree so unimportant that, like the earthquakes of volcanic origin, they hardly come into comparison with the disastrous or destructive shocks. As a result of his exhaustive statistical researches, De Montessus says: "While we may cite regions frequently shaken by earthquakes which at the same time have very active volcanoes, the fact should be recognized that *there is independence of the seismicity and volcanicity.* . . . There is coincidence between the unstable regions and eruptions . . . but one phenomenon does not in a marked degree cause the other."

Perhaps the mutual relationship of volcanic eruptions and earthquakes may be best expressed by saying that *there is no quick response of the one phenomenon to the other.* If, however, the volcanic and seismic histories of the same province be compared throughout long periods, it is found that a certain correspondence obtains between the periods marked by excessive volcanic activity and those of unusual earthquake intensity. During the great Calabrian earthquake of September 8, 1905, the greatest

in more than a century for that classic province, the neighboring volcano, Vesuvius, showed not the slightest sympathy. Eight months later, however, there occurred in it the grandest eruption in almost three centuries. Going back to the even greater earthquake in Calabria in 1783, we find that both Etna and Vulcano, within the same province, betrayed a distant relationship in time to the earth shakings. Study of the West Indian region reveals also the same general relations between earthquakes and volcanic eruptions. Sometimes it is the eruption which precedes, at other times the earthquake; and it is possible to conceive that the settlement of blocks within the earth's crust manifested by earthquakes may, by the transformation of the energy of motion into heat, melt and squeeze out portions of the underlying rocky material. It is an equally plausible assumption that the extrusion from the surface of the earth of large quantities of rock material may cause a tendency toward settling or subsidence, which eventually would bring about an earthquake.

Earthquakes and mountain systems. The association of earthquakes with mountainous districts was early noted, and the Italian seismologist, Baratta, has justly laid stress upon the fact that it is with the mountains which arose in the Tertiary age—the latest great period of mountain building—or those which increased their height in that period, that instability is especially connected.

Relation of earthquakes to former and existing ocean basins. One of the most interesting of the generalizations which De Montessus has reached as a result of his protracted studies, is that the earthquake districts on the land correspond almost exactly to those belts upon the globe which were the almost continuous ocean basins of the long Secondary era of geological history. Within these belts the sedimentary formations of

the crust were laid down in the greatest thickness, and the formations follow each other in relatively complete succession. For almost or quite the period of this long era it is therefore clear that the ocean covered these zones. About them the formations are found interrupted, and the lacunæ indicate that the sea invaded the area only to recede from it, and again at some later period to transgress upon it. For a long time, therefore, these earthquake belts were the sea basins—the geosynclinals. They became later the rising mountains of the Tertiary period, and mountains they are to-day. The earthquake belts are hence those portions of the earth's crust which in recent times have suffered the greatest movements in a vertical direction—*they are the most mobile portions of the earth's crust* (see Figs. 15 *b* and 16 *b*).

The geosynclinals, which in a broad way we may trace upon the continents in the courses of mountain systems, are ranged along the margins of the existing oceans, and observation has shown that, except where the great delta regions of rivers are heavily overloading the crust and causing it to settle, the shore lines are being elevated and the mountains pushed up often at a quite astonishing rate. To correspond with this elevation of the land along the coast, the near sea bottoms are being depressed so as to maintain a certain balance between the two. Frequent and intense as are the earthquakes upon the continents, they are far more violent on the steep margins of the ocean deeps. Naturally our information for these under-sea areas is less complete, but as a result of the new and "distant" methods by which earthquakes are now being studied, facts are rapidly being gathered, and have already supplied a fairly decisive verdict for the greater relative seismicity of the under-sea portions of the earthquake zones.

Recapitulation. To bring into review the broader generalizations of seismic geography, it may be stated that the earthquake districts upon the continents correspond in their distribution (1) to that of the Tertiary mountain systems, or to mountain systems which have increased their height materially during and since the Tertiary period, and to the neighboring country; (2) to zones bordering the coasts; (3) to the regions within which active volcanoes are found; and (4) to the most mobile portions of the earth's crust. The mobility of the earthquake zones is demonstrated not alone directly through the shocks themselves, but indirectly also by their occupation as sea basins depressed below the general level during the Secondary era, and their elevation above it as the mountain systems of to-day.

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CHAPTER IV

EARTHQUAKE FAULTS AND FISSURES

THE appearance of fissures in the ground has been a characteristic of all greater earthquakes. The number of such fissures has often been legion, and they have ranged in size from mere cracks a few feet in length to great rifts which have been followed for a hundred miles or more. It is customary to describe as faults those fissures only upon which a measúrable displacement of the two portions of ground separated by the fissure is observable.

Large faults are relatively few.

An earthquake fault, which may manifest itself as a fresh earth or rock wall leading up to a terrace where the ground has been raised, while often described, is not the most common form. Such faults of exceptional dimensions have been formed in connection with the Mino-Owari (Japanese) earthquake of 1891 (see frontispiece plate and p. 151) and the great Assam (Indian) earthquake of 1897 (p. 160); and in our own country in connection with the Owens Valley earthquake of 1872 (p. 179); the Sonora earthquake of 1887 (p. 183); the Yakutat Bay (Alaskan) earthquake of 1899 (p. 188), and the California earthquake of 1906 (p. 195). In contrast with the fissures and smaller displacements, the number of these large faults is generally small, more than two having been seldom described in connection with any single earthquake disturbance.

Some of the longest displacements, or perhaps one should say those which have been followed for the longest distance, are those of the Neo Valley in Japan (1891), and of California (1906). The first-mentioned was traced for more than forty miles, and the latter from two hundred to three hundred miles.

Characteristics of the faults. The principal faults formed at the time of earthquakes generally either keep to a definite direction, or make relatively sudden turns, as did, for example, the faults formed in connection with the earthquake of Northern Honshu (Japan) in 1896. Those formed during the shocks of the Sonora earthquake of 1887, made

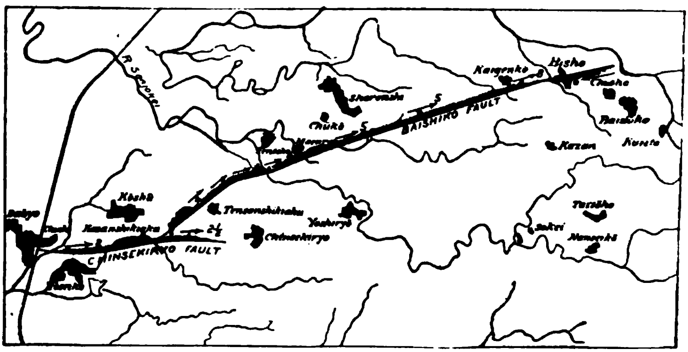


Fig. 18.—Map of the fault formed during the earthquake in Formosa, March 17, 1906 (after Omori).

also sudden bends, and it was noted that cracks extended out from the "elbows" as continuations of the original directions. This feature is also exhibited by the Formosa fault of March 17, 1906 (see Fig. 18).

The study of Japanese earthquakes has shown that an up-and-down displacement upon the fault reveals itself as a steep wall of freshly fractured earth or rock when-

A. Parallel step faults at the base of the Alabama Hills. The courses of the faults can be followed by the efflorescence of white salts upon them.

B. A zigzag in the course of one of the faults near Lone Pine. In the foreground the course of the faults is outlined by the slope on which the large boulders are found. The change in direction takes place in front of the dark hill in the middle distance.

FAULTS PRODUCED IN THE OWENS VALLEY, CALIFORNIA, DURING THE EARTHQUAKE OF MARCH 26, 1872. (After photographs by W. D. Johnson.)

ever the displacement measured at the surface much exceeds two feet. When less than this amount, the displacement is more frequently revealed as a rounded step or terrace crossed by transverse fissures, and bearing some resemblance to the track of a mole, save for its larger dimensions (Plate XX, *B*). Such effects were produced in connection with the recent California disturbance. So common are such phenomena in Japan that the superstition has grown up that a gigantic catfish moves beneath the surface at the time of earthquakes. Upward-and-downward displacements which are measured in inches only are often difficult to determine, and appear either as open fissures, or are indicated by the derangement of the surface drainage within the district affected.

Nature of the movement on earthquake faults.

So far as the movement along an earthquake fault is upward and downward, it appears to take place upon nearly or quite vertical planes. No evidence of the overriding of the one part by the other, the inevitable result of movement upon a sloping plane, has as yet been reported. There is, however, ample evidence that the earth block or blocks lying upon the one side of the fault sometimes slip laterally past those upon the other side. Such a movement may take place with little or no vertical movement, or the two movements may have occurred upon the same plane. Probably in all cases there is some movement, both vertically and laterally, with variation between the widest limits in the relative proportions of the movements along the two component directions. The significant fact appears to be, that *movement along any plane which crosses the fault line* (except in case of the intersection of faults) *seems not to have been observed.*

The above-described motions may be illustrated by plac-

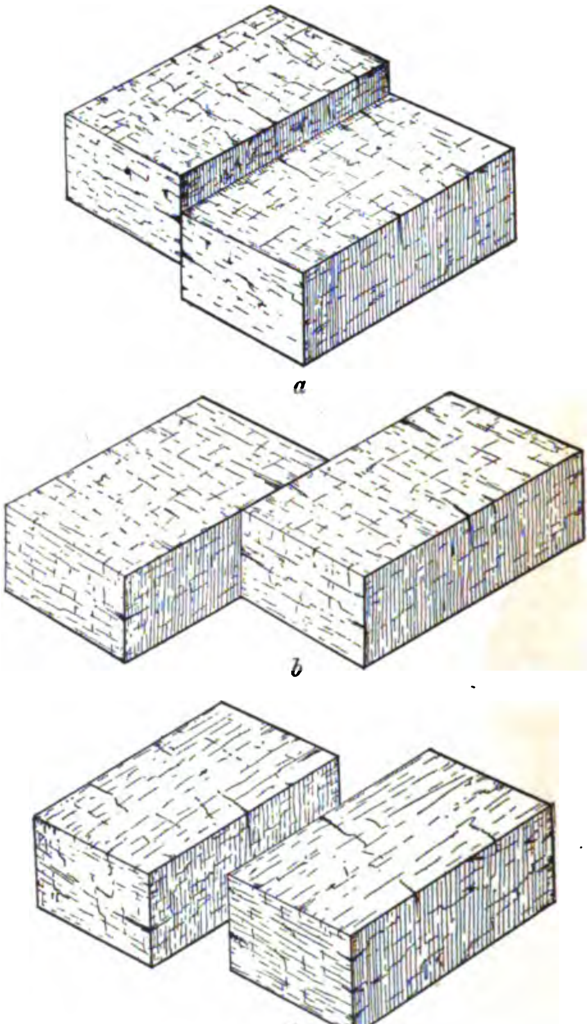


Fig. 19, *a–c*.—Views to illustrate the movement of earth blocks upon earthquake faults.

ing two squared blocks cut from planking beside each other and (1) by raising one of them with reference to the other through a small fraction of its thickness (Fig. 19, *a*), (2) by sliding one past the other through some fraction of its length (Fig. 19, *b*), and (3) by sliding and raising the one with reference to the other either by a single or by two separate movements (Fig. 19, *c*).

[M]agnitude [of] the dis[pla]cements. The observations which have thus far been made go to show that the magnitude of the movements in the vertical and horizontal directions along fault planes are of the same order. The maximum recorded movements upon faults have apparently stood in some relation to the magnitude of the earth shocks in the vicinity. During the great earthquake in Iceland in 1875, the depression of Sveinagja sank between faults a maximum distance of more than sixty-five feet. During the great earthquake in Alaska in September, 1899, vertical elevations of as much as forty-seven feet were brought about, but it is not certain in either of these instances whether the displacement was upon a single plane of faulting or was distributed over several planes within a zone (see Fig. 26, p. 78). The vertical displacement upon the Chedrang fault produced during the Assam earthquake of 1897 was in one place no less than thirty-three feet, and that of the Mino-Owari earthquake in Japan in 1891 was, at Midori, about eighteen feet (see Frontispiece). A vertical displacement of twenty feet was reported upon faults dating from the Indian earthquake of 1818, from the Owens Valley (California) earthquake of 1872 (see Plates IV and XVII, and Fig. 23), and from the Sonora earthquake of 1887.

Horizontal shiftings to cause displacement along earthquake faults have in a number of cases been reported. A

displacement of this nature amounting to eight and one-half feet occurred on a fault in New Zealand in 1888. One of thirteen feet was reported along the Neo Valley fault of Japan in 1891 (see Fig. 20), and one of fif-

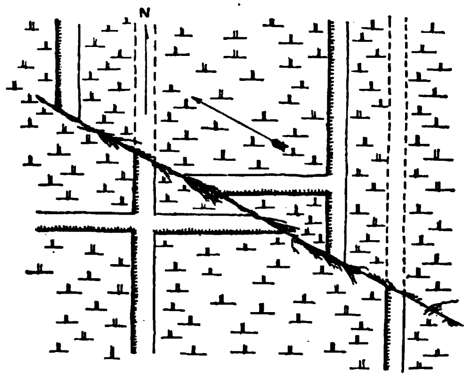


FIG. 20.—Neo Valley fault of Japan (October 28, 1891) where it cuts the paddy fields. With slight vertical displacement only (northeast side dropped) the low ridges which separate contiguous fields are laterally displaced (after Kotô).

teen feet along one of the faults in the Owen's Valley in 1872. The largest reported displacement of this character is that upon the great rift line of California, on April 18, 1906, which at one place was no less than twenty feet (see Plate VI, *A*, and XX, *A*). In this latter instance the horizontal displacement was much in excess of the vertical, which rarely, if ever, exceeded four feet. On the other hand, the maximum vertical displacement upon the Neo Valley fault was as large as or larger than the horizontal (eighteen feet at Midori). In places, however, a large horizontal shifting was unaccompanied by vertical throw (see Figs. 20 and 57). The earthquake in Kagi Prefecture in Formosa, which occurred March 17, 1906, was accom-

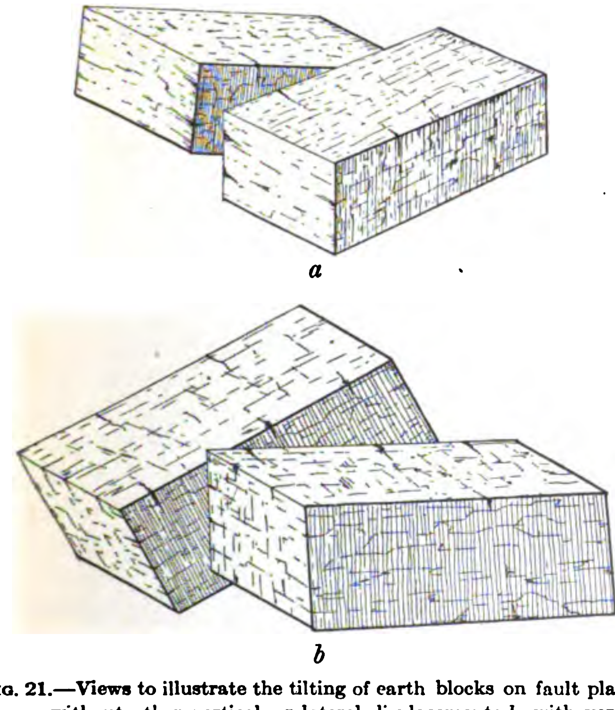
A. END OF A PIER AT INVERNESS (TOMALES BAY), CALIFORNIA, WHICH WAS DISPLACED TWENTY FEET DURING THE EARTHQUAKE OF APRIL 18, 1906. (After Omori.)

B. THE BAISHIKŌ FAULT FORMED IN FORMOSA DURING THE EARTHQUAKE OF MARCH 17, 1906. The foreground has sunk six feet and been displaced six feet toward the left in the view. (After Omori.)

panied by maximum displacements of six feet vertically and eight feet horizontally. Apparently the proportion of the one to the other component of movement upon earthquake faults varies between the widest limits.

idences ilted cks.

The fact that the principal movements upon earthquake faults take place either vertically, upward or downward, or laterally along the line of displacement at the surface, furnishes a somewhat decisive verdict concerning the attitude of the plane of dis-



a

b

Fig. 21.—Views to illustrate the tilting of earth blocks on fault planes: *a*, without other vertical or lateral displacement; *b*, with vertical and lateral displacements.

location with reference to the surface of the earth. Both these movements can take place together only upon a vertical plane, and the only other movement which is conceivable upon such a plane is a differential tilting of the blocks about an axis normal to the fault plane (see Fig. 21). Were the plane other than vertical, movement upward or downward must inevitably make the land upon the one side of the fault override that upon the other, as is clear from Fig. 22. It is significant that such an overriding has not yet been observed.

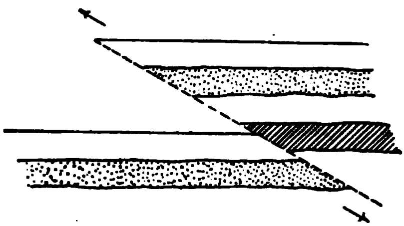


FIG. 22.—Diagram to illustrate how overriding must occur upon inclined faults.

While tilting of the land upon one side of the fault, about an axis normal to the fault plane, is a possible form of motion with vertical faults, it must be small in amount in blocks which are parts of a continuous surface that is further subject to noteworthy compressional stresses directed parallel to its surface. That small tiltings of this nature do occur has been demonstrated by observation, and it is further probable that the extensive derangements of the surface drainage at the time of earthquakes is in considerable part to be ascribed to such tiltings. Inasmuch, however, as these tiltings involve large surface areas, they represent angular movements of a few degrees only at the most. Larger movements of the same kind would involve a degree of crushing upon bounding fracture planes due to compression at the surface which has not, as yet, been observed.

By far the most remarkable instance of the tilting of

the earth's surface in the vicinity of an earthquake fault, is that which was described in connection with the Indian earthquake of 1897 (see p. 164).

planation opening d closing fissures.

It has been stated above that the amount of compression exhibited in the vicinity of earthquake faults in the direction normal to them does not require any considerable angle of tilting in either of the earth blocks which meet at the fault plane. It has many times been reported by reliable observers that earthquake fissures have opened in such a manner as to engulf and cover houses, cattle, and even men, and that these objects have in some cases been subsequently ejected through a reopening of the fissure. Humboldt tells us that during the great earthquake of Riobamba, which occurred on February 4, 1797, men were caught in fissures which opened in the ground beneath their feet, but closed quickly with violence, so as to pinch the lower part of the body, but leave the trunk and upper extremities free. These and other accounts, despite the high authority and scientific reliability of the narrators, appear to have been rather generally discredited in the past, and for no other reason than that they did not find an adequate explanation in the existing theory. Examined with care, however, and in the light of newer conceptions of the cause of earthquakes, they are found to be not only fully verified as facts, but susceptible of a simple explanation.

The scientists of the Naples Academy, in their report upon the great earthquake of Calabria in 1783, state that men and animals were alike engulfed in the fissures formed during the earthquake, and that these fissures first closed upon them and afterwards ejected them. This statement becomes at once credible when we read the further statement that the bodies were ejected together with large vol-

umes of water and sand, both of which are now known to be squeezed out through fissures in large quantity in connection with all great earthquakes. Some of the houses which were in like manner swallowed by the fissures of the Calabrian earthquake, were afterwards exhumed and found to have been jammed together as though they had been made of pasteboard. The great Round Tower of Terranuova was by the same earthquake faulted with vertical displacement, and the two separated parts so ground and welded together that the wound along the fault was revealed only by the failure of the stone courses to match.

Some of the movements on fissure planes of the nature just described would appear to have been relatively rapid, while others were notably slow. Certain fissures in Calabria, of which the lips gaped wide when examined by the academicians on their outgoing journey from Naples, had wholly or partly closed before the return from their tour of investigation. A slow reopening of some of these fissures was also confirmed, and appears to have differed in rate of motion only from those sudden movements which ejected the buried objects enveloped in great volumes of sand and water.

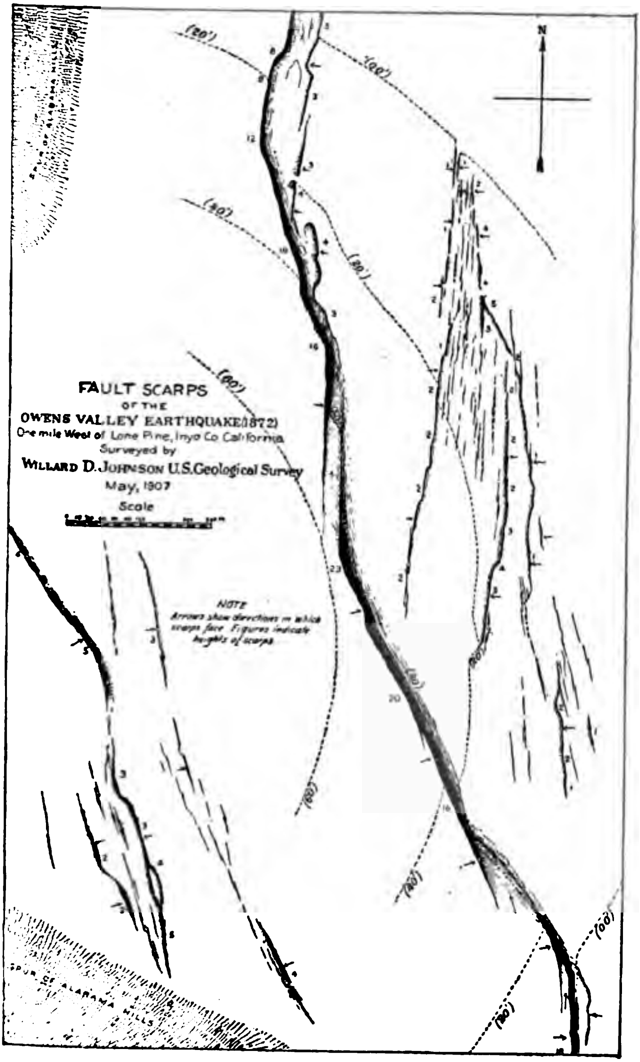
The retreating faults of the Owens Valley.

Mr. W. D. Johnson, of the United States Geological Survey, has, during the season of 1907, made some very interesting observations upon the faults produced in Owens Valley, California, in 1872, and at the time of earlier earthquakes within that district. These observations he has, with great generosity, placed at the writer's disposal for study. His map of the faults opened during the earthquake of 1872, which in part is reproduced in Fig. 23, constitutes one of the most important contributions yet made to seismology. Mr. Johnson

A. Gaping fissure in one of the streets of San Francisco from which the disturbed surface of the ground tilts outward.

B. An area on Valencia Street, San Francisco, which was dropped and shifted laterally about ten feet. The damaged structures were consumed by fire.

DISPLACEMENTS OF THE EARTH'S SURFACE IN CALIFORNIA DURING THE EARTHQUAKE OF APRIL 18, 1906. (After photographs by Fairbanks.)



N
FAULT SCARPS
OF THE
OWENS VALLEY EARTHQUAKE (1872)
One mile West of Lone Pine, Inyo Co California
Surveyed by
WILLARD D. JOHNSON U.S. Geological Survey
May, 1907
Scale
NOTE
Arrows show directions in which scarps face. Figures indicate heights of scarps.
SPUR OF ALABAMA HILLS

FIG. 23.

finds it to be a characteristic of these faults that after maintaining a constant direction for a longer or shorter distance, they begin to die out through a gradual diminution of the displacement, and that simultaneously a small displacement makes its appearance upon a neighboring parallel fissure and increases its throw at a rate approximating to that at which the other disappears. It follows that about opposite where the first has died out the second has acquired its full displacement. Normally, these faults produce flat terraces, but within the area in which the displacement is transferred from the one fault to the other, a sloping surface inclines in that direction which continues

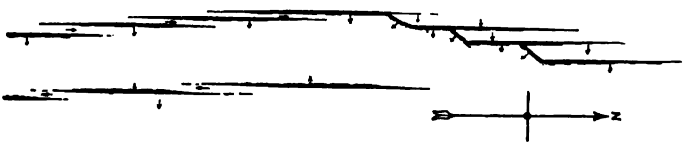


FIG. 24.—Parallel faults of the Owens Valley, California, where a displacement is transferred from one plane to a parallel one (after a diagrammatic sketch by W. D. Johnson).

the fault that has died out (see Fig. 24). Sometimes it happens that such faults are arranged *en echelon*, like the wings of a theater, in which case the combined zigzagging displacement is in effect the equivalent of one which has a general course passing through the centers of the several sections of faults, and having a hade at a relatively flat angle in the direction of the down-thrown blocks. Within the transitional zone, where the displacement is transferred from one fault to another, small earth blocks are clearly tilted, and they produce a topographical effect like that where a road climbs diagonally the steep slope bordering a low terrace through excavation upon the one side

and filling upon the other. Between such short tilted blocks, arranged in series and separated by fault scarps of varying displacement, and certain "mole-track" displacements which develop in connection with many earthquakes, there exists a somewhat close relationship. In fact, it will appear that the two phenomena differ mainly in the scales upon which they are developed, and it is likely that the explanation of each is alike to be found in the existence of parallel fractures on which slips take place with a maximum of ease. This direction is that of the longer continuous displacements. The transverse fissures which locally appeared upon the California rift (see Fig. 25) are susceptible of essentially the same explanation, there being here at least two such directions of easily adjustable fissure planes.

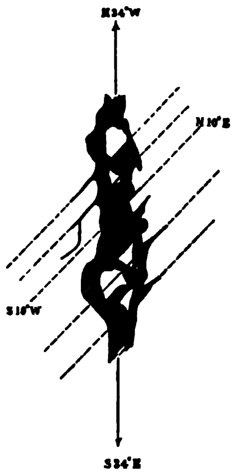


Fig. 25.—Parallel fissures transverse to main California rift. Earthquake of April 18, 1906 (after Omori).

Amount and direction of displacement not uniform along fault.

It is a fact of much significance, but one to which too little attention has been given, that the amount and the direction of the vertical displacements upon a fault vary through wide limits and with great abruptness. This fact was especially well brought out by the Chedrang fault of 1897 (see p. 162, and Fig. 60), as also by the displacements along the shore of Yakutat Bay, due to the adjustments of September, 1899 (see p. 191, and Fig. 68). Such conditions require us to conclude that the earth upon the two sides of the fault plane belongs not to two individual blocks only, but that

a number are ranged upon either side, separated from their neighbors by other fault planes which meet the visible one at the points of sudden change in displacement. The same explanation accounts for the sudden disappearance of earthquake faults and their reappearance on a continuation of the same direction after a longer or shorter interval of undisturbed ground. Such an interrupted character in an earthquake fault was especially well shown by the faults dating from the earthquake of Sonora in 1887, and the Japanese earthquake of 1896 (see p. 168), but is of rather general application.

The Neo Valley fault (Japan, 1891) trended from northwest to southeast, and it was generally true that the northeast side was displaced toward the northwest, though the reverse movement was also in at least one instance observed. The northeast side was also the one which was generally dropped down. At Midori, however, the maximum drop occurred (eighteen feet), and here of the land *upon the southwest side of the fault.* The movement on the great California rift during the latest earthquake in the district was mainly a lateral one, which shifted the land upon the northeast side toward the southeast. On the west coast of Tomales Bay, however, a displacement in the opposite direction amounting to no less than twenty feet was recorded by an abrupt offset upon the pier at Inverness (see Plate V, *A*). This exceptional displacement is almost equal in amount to the maximum displacement in the opposite and usual direction. In the southern portion the vertical displacement appears to be the reverse of the usual one, from which it is separated by a zone of inappreciable throw.

These abrupt changes in the displacement upon fault planes, so far as they relate to vertical movement (throw),

are accounted for by vertical adjustments of earth blocks which have one side in contact with the visible fault, and whose other faces meet upon fractures which may or may not appear as open fissures, but whose intersections with the visible fault are indicated by the points where greatest change in displacement is to be observed along it. Upon the shores of Yakutat Bay the observations made seem to show that these abrupt changes of the displacement are marked by transverse valleys crossing the general course of the fault (see Fig. 68).

Explanation of opposed shiftings on fault plane.

The lateral shiftings which cause displacement upon a fault line are probably to be explained through variations in compactness of the material upon the two sides. It does not need to be demonstrated that open spaces within surface rocks amounting in the aggregate to quite appreciable percentages of the total volume generally exist. Much of this space is found upon the omnipresent joint or fissure planes which are the trunk channels for the circulating water. The closing of such fissures through excessive compression exerted upon the one side only of a fault, must bring about notable lateral discordance, observable at the surface. Sudden changes in such lateral displacements, comparable to the frequent changes in vertical displacement, would be rather difficult to account for, and as yet appear not to have been described.

Habitual earthquake faults.

Faults are planes of weakness in the earth's crust, and they become the seats not of one, but of a series of interrupted movements, each of which is more or less strongly manifested as an earthquake. Such a plane of weakness traverses the southern border lands of Afghanistan and Beluchistan; our knowledge of it dating, however, only from studies made after a notable earth-

quake on December 20, 1892. For no less than one hundred and twenty miles, all of which was carefully surveyed, a well-defined broad line of deep indentation upon the surface was followed, and was in places as clearly defined as a deep railway cutting. Its course crosses mountain ranges at prominent passes, or it takes its way along valleys quite independent of the larger features of the country. Along its entire course are to be found springs of water, and on this account, as well as because it is a natural short cut, it has been utilized as a thoroughfare. The old graybeards of the tribes living along it say that three times during their lifetime deep fissures have appeared along its course, and similar accounts of earlier occurrences have been handed down to them from their grandfathers. After one of these occurrences the springs were found to be largely augmented in volume. This line is clearly a fault line, and all the rocks to the east of it are sedimentary in origin, while those upon the other are igneous. Near Quetta a large movement upon this rift occurred at the time of the earthquake of December 20, 1892.

Lines of rifting in the earth's crust like the one just described are probably far more numerous than has generally been supposed, since their significance is now, for the first time, coming to be appreciated. A similar line to that in central Asia is the *fossa magna,* which crosses Japan from south to north near the bend or "elbow" of the larger island. This rift is a furrow leading from sea to sea, which has become a thoroughfare of the first importance, and is recognized as a line of faulting. Movements along it have not as yet been connected with definite earthquakes, but there can be no doubt that it has played this rôle in the past, and is likely again to do so in the

future. At any moment an earthquake may arrive which will reveal to all its true significance.

The rift valleys of eastern Africa and of California.

A great rift valley, with several branches, has been traced in central and northern Africa, and continues through the valley of the Jordan in Asia Minor. The great earth rift which traverses California has been clearly recognized as the seat of earth movement since the disastrous shocks of April 18, 1906. For more than three hundred miles its course has been traced across mountain range and valley or barren desert (see Fig. 70), and along much of the distance movement occurred at the time of the recent earthquake. With much probability this great rift is extended across the Gulf of Lower California, and continues in the great valley along the western base of the scarp which limits the Mexican plateau. The earthquake of April 15, 1907, was localized in this part of the rift, and may be considered as an extension of adjustments which were begun not quite a year earlier in California. The fissures which opened during the earthquakes in the Amuri district, New Zealand, in the months of September and October, 1888, were all along old fractures, as were also many of those which opened in the Owen's Valley, California, in 1872.

The smaller faults and fissures.

It has been stated that the faults of the first order of magnitude have, for by far the greater number of earthquakes, been relatively few. Faults which are measured in fractions of a foot at the surface of the earth, hardly differentiate themselves in any important way from fissures, with which, therefore, they are classed indiscriminately. They are often numbered literally by the thousands, in the case of large earthquakes, as, for example, the Charleston earthquake of 1886, and they run in many directions. They are distinguished from the

larger faults by their small or inappreciable displacements, and, usually, by their less considerable extensions. They play a most important rôle as the trunk lines for the temporary subsurface flow of water, sand, and mud, which almost invariably begins with the advent of the earthquake (see Chap. VII). They are also, in many instances, the channels for transmission of gases emitted at the surface. Such gases are generally highly charged with sulphureted hydrogen (due to the decomposition of animal and vegetable matter in the soil) and are disengaged by the local fissuring.

Arrangement of fissures. Earthquake fissures, like earthquake faults, have been often observed in parallel series; as, for example, at Sinj in Austria, after the earthquake of 1898, where, owing to small progressive displacements, a series of small steps or terraces came into existence in the surface (see Fig. 26). At other times a network of fis-

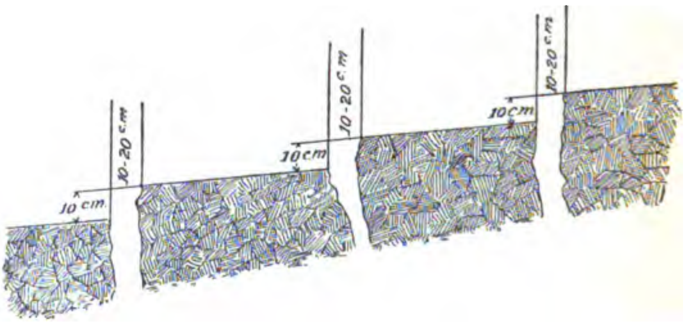


FIG. 26.—Small terraces, due to parallel fissures in the ground. Earthquake of Sinj, Austria, in 1898 (after Faidiga).

sures has been observed, as, for example, at Aigion (Vostizza) in the Balkans, after the earthquake of December 26, 1861 (see Fig. 50, p. 133). Such a network was described, also, by Whitney in the Owens Valley, after the

earthquake of 1872. Whymper tells us that in Ecuador great earth fissures are among the most common features of the Andes, are generally recognized as earthquake cracks, and are called earthquake *quebradas.* Speaking of Cotocachi, he says: "In no other part of Ecuador is there anything equalling this extraordinary assemblage of fissures, intersecting one another irregularly and forming a perfect maze of impassable clefts. . . . The cracks are all V-shaped, and though seldom of great breadth, are often very profound, and by general consent they are all *earthquake quebradas.* Several, at least, have been formed within the memory of man, while others are centuries old."

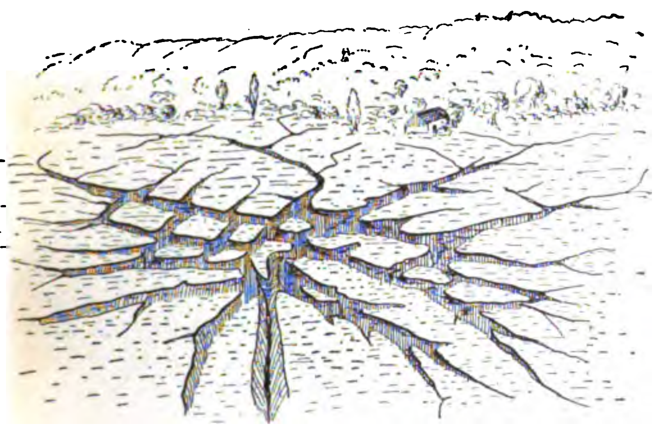


FIG. 27.—Radial cracks in the surface of the ground formed during the Calabrian earthquake of 1783, at Gerocarne (after Lyell).

Sometimes earthquake cracks in the ground have appeared to radiate from a center, as, for example, at Gerocarne after the Calabrian earthquake of 1783 (see Fig. 27). At other times such radial cracks went out from a more or less circular depression in the ground, occupied

either by a pool of water or by sand (see Fig. 28). **Radial cracks like those formed at Gerocarne were produced in compact limestone upon the sea bottom in the vicinity of Zante, Greece, during one of the numerous earthquakes**

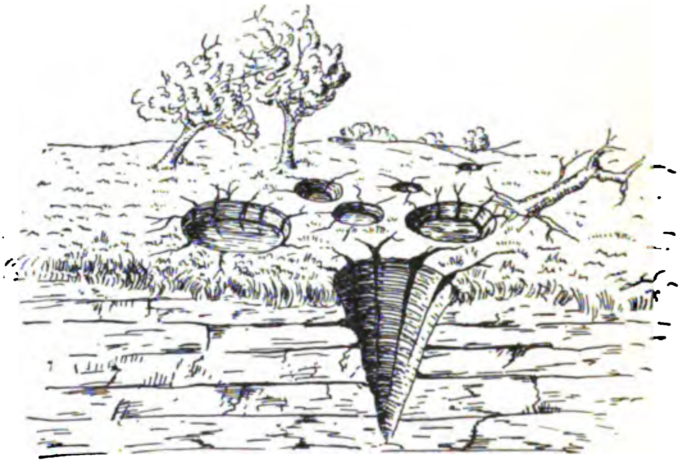


FIG. 28.—Radial cracks about pools of water formed during the Calabrian earthquake of 1783, at Rosarno.

of that unstable region. Their discovery was made while repairing the telegraphic cable ruptured at the time of the earthquake.

Relation of faults and fissures to topographic relief.

It was observed by the French geologist, Dolomieux, who visited Calabria shortly after the great earthquake of 1783, that the directions of the newly developed fissures were in most cases parallel to the preëxisting ravines and gorges. This was likewise a characteristic of the great earthquake in Chemakha, Turkestan, on February 13, 1902, when trough-like depressions were produced by the opening of fissures on op-

posite sides of valleys. There is much probability that such faults of small displacement are very frequently located along river valleys, but lie buried under river sediments, and become manifested at the surface by the so frequent landslips along the banks.

It was noted also after the great Calabrian earthquake that the largest fissures followed the bases of the mountain ranges which were also the boundary planes between the more crystalline rocks of the mountain masses and the unconsolidated or loosely consolidated materials which formed the valleys. A general coincidence between the course of earthquake faults and the bases of steep ranges of mountains was also characteristic of the Owens valley earthquake of 1872, the Sonora earthquake of 1887, and the Japanese earthquake in northern Honshu of 1896.

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CHAPTER V

THE NATURE OF EARTHQUAKE SHOCKS

THE nature of the disturbances to which objects are subjected during earthquakes merits careful attention, and appears to stand in some relation not only to distance from a fault line, but also to the nature of the fault itself—whether largely due to a movement of vertical displacement, or to one of lateral shifting on the course of the fault. Observations to be reliable should be made at points relatively near to the larger visible displacements, since otherwise one is left in doubt as to how much of the disturbance observed should be ascribed to movements emanating from the visible displacement, and how much to movements on nearer hidden faults of smaller displacement.

Movements which are largely mechanical.

Some of the movements which are transmitted to objects in the immediate vicinity of a fault, appear to be due either to the removal of support, or to the inertia of rest of bodies which are suddenly subjected to movement. Where a fault has passed beneath a wooden structure of small rigidity, the fault has merely passed upward through the building to produce a shear like that in the underlying crust. A barn, located over the main rift at a point where it underwent a vertical displacement, was thus faulted by the California earth-

quake of 1906 (see Plate VII, *B*). Had the structure possessed greater rigidity, it would have undergone a tilting through a small angle, and might, perhaps, have been overthrown. A block of granite forty feet long, thirty feet wide, and thirty feet high, which had lain over the course of the Chedrang fault opened in India in 1897, was completely overturned. In this case, not only the removal of support upon the one side of its center of gravity, but the sudden lift upon the other, which was the upthrown side of the fault, accounts for the overturning.

When the shearing motion upon the fault plane is mainly in a direction along the surface of the ground, a very different effect is produced. Here the inertia of rest of the body is responsible for its remaining behind when the portion of earth on which it had rested moves out from under it. Excellent illustrations of this have been furnished from the California earthquake of 1906, by a house which shows the underpinning exposed for some three feet of its surface where the superstructure has lagged behind. There is here no need of a visible fault to prove that the earth has suddenly moved in that direction indicated by the movement of the underpinning (see Plate VII, *A*).

Successional shocks. Mechanical disturbances such as have been described in the above paragraphs are not, however, the only ones which cause damage in the neighborhood of earthquake faults. If the fault in question be one of vertical displacement, the one portion of the two into which the earth's crust is severed by the fault suddenly slips over its neighbor, only to be as suddenly arrested. The motion is best described as a jolt or shock, and must be accompanied by a sharp reaction, which, checked in like manner in the opposite direction, must

A. House which slid upon its foundation a distance of four feet.

B. Barn which was tilted over a fault and dragged about ten feet.

DISPLACEMENTS OF BUILDINGS DURING THE CALIFORNIA EARTHQUAKE OF APRIL 18, 1906. (After photographs by Fairbanks.)

give rise to a series of successional waves. These successional shocks are characterized above all by their great amplitude (great intensity) and by their slow period. There is substantial agreement among reliable observers who have experienced earthquakes either near a fault or over a strong seismotectonic line, that the earth is first bulged upward into a swell which appears to move outward along the surface, thus fulfilling all the conditions of simple harmonic motion. Neither men nor animals are able to keep their feet, and a sensation of nausea is induced, just as it is in a vessel rocking upon the waves of the sea. The passing clouds appear to be arrested, as they do also when observed from the deck of a tossing vessel.

In the case of the New Madrid and some other earthquakes, the ridges which were first raised in the ground were seen to open and the fault thus come suddenly into view.

The "Sbalzo."

The academicians of Naples, who described the great Calabrian earthquake of 1783, tell us of a bounding of objects into the air, which was described as the *Sbalzo*. In certain of the Calabrian towns a good part of the paving stones were projected for some yards into the air and were afterwards found lying with their lower sides uppermost. Von Humboldt reported that during the earthquake of Riobamba in 1797, bodies were projected out of their graves, and up from the earth's surface. During the Icelandic earthquake of 1896, persons lying upon the ground near the edge of a cliff were projected bodily into the air and over the edge of the cliff. During the great Indian earthquake of 1897, large bowlders were thrown up from the ground and left, after their fall, with the dirty side uppermost (see Fig. 61 p. 164).

The succession of these upwardly directed shocks is felt by persons as a thumping against the soles of the feet, and was so reported by residents of Charleston during the earthquake of 1886. Under such a bombardment of shocks the inertia of heavy bodies resting upon the ground causes them to be depressed into the earth. Stone posts are, in favorable localities, quite generally found surrounded by a narrow pit like that about a rod which is immersed in a bath of mercury (see Fig. 29), and heavy

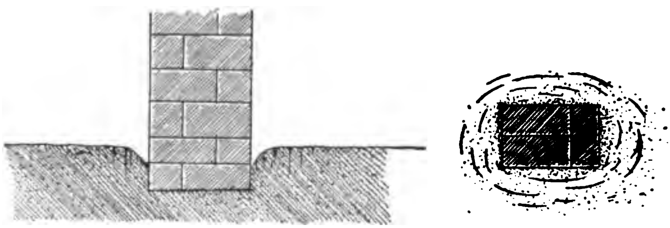

Fig. 29.—Heavy posts sunk into the ground during the Charleston earthquake of 1886 (after Dutton).

monuments have been half buried in the earth, as, for example, during the great Indian earthquake of 1897.

Longitudinal successional shocks. Our best knowledge of the effect of a lateral shifting of the ground along a fault has been furnished by the California earthquake of 1906, since of this earthquake, more perhaps than of any other, is it true that the motion upon the fault was mainly a longitudinal one. The great vibrations of the ground in the vicinity of the California rift were most strikingly manifested in the swaying of the trees, which under the influence of the shocks fairly lashed the ground with their branches. Those of a more brittle wood were snapped off, but others again regained their original attitude after the shocks had passed. Tanks of water which were located near the fault

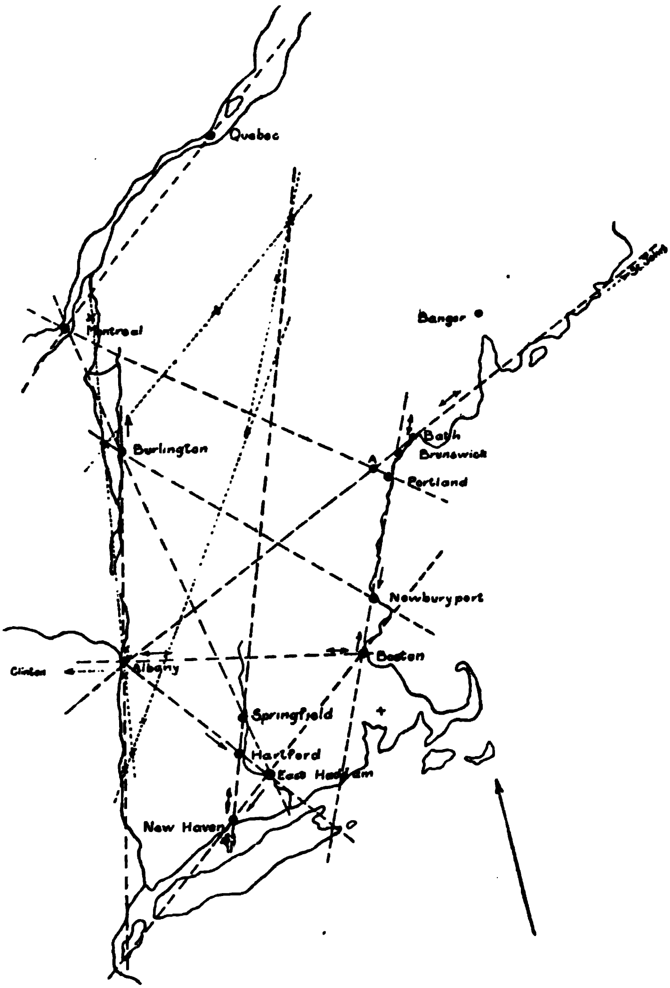

Fig. 30.—Sketch map to show the seismotectonic lines and the local directions of heavy shocks felt in connection with the earthquake of October 20, 1870, in New England. The dark spots show where the shocks were felt, the arrows their direction, the small crosses where small faults of post-glacial age have been observed.

spilled over so as to be nearly or quite emptied. The vibrations of the trees and of the water surfaces in the tanks were alike *along the direction of the fault.* Such a movement, also, was characteristic of the fault opened in connection with the great Formosa earthquake of 1906 (see Fig. 18, p. 62), on which a lateral movement of eight feet was measured. Essentially the same facts have been brought out for certain earthquakes which have produced no extended open fissures. The earthquake in Calabria in 1894, in New England in 1870, and in Jamaica in 1907, all disclose the same relations between the heavy shocks and the direction of the fissures, in these cases, however, buried beneath the surface and represented only as seismotectonic lines (see Fig. 30).

Observations have been made at considerable distances (several miles) from great earthquake faults, and conclusions drawn from them respecting the direction of the shocks with reference to the fault. We are here upon very uncertain ground, since we are not assured that the distant visible fault is the one to which the local effect is solely, or even mainly, to be ascribed. Waves of some sort are beyond question transmitted outward in every direction from the entire surface of all fault planes, but extended studies upon Calabrian earthquakes seem to indicate that the energy thus transmitted in directions transverse to the fissure is impotent against structures after traveling for a mile or two, and that cities fortunate enough to be located well away from the principal faults remain for centuries practically immune from destructive shocks, even though in the heart of an earthquake district.

Wherever fault lines intersect upon the surface, the successional shocks mentioned above must reach the same

point from two or more directions (see Fig. 31). The effect of the one being here added to that of the other, the result is the more disastrous to structures, and this not alone by reason of the augmented intensity, but because the additional directions of movement furnish the means for searching out the weaker elements in construction. Some buildings, by virtue of peculiarities in construction, are able to withstand heavy shakings from one quarter, but would quickly

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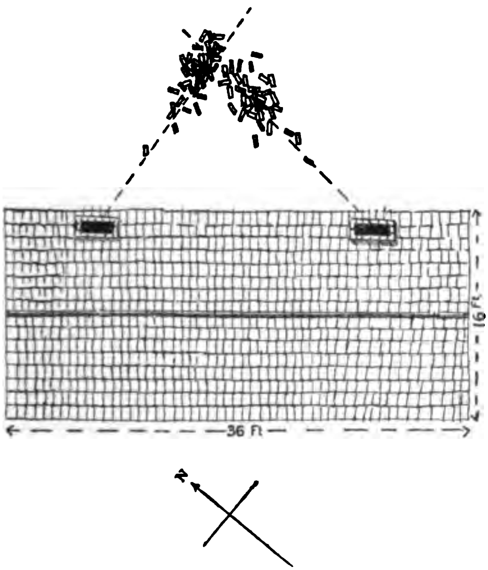

FIG. 31.—Plan of house at Charleston. Earthquake of August 31, 1886. The bricks thrown from chimneys show that heavy shocks came from two directions—the one south, the other west (after Dutton).

collapse were the direction of the attack to be materially altered.

Registration of the combined motion.

We may, perhaps, best illustrate the manner in which earthquake shocks are combined at fault intersections if we set up two tuning forks and sound them together. By attaching small mirrors to their vibrating extremities, and directing a ray of light first to

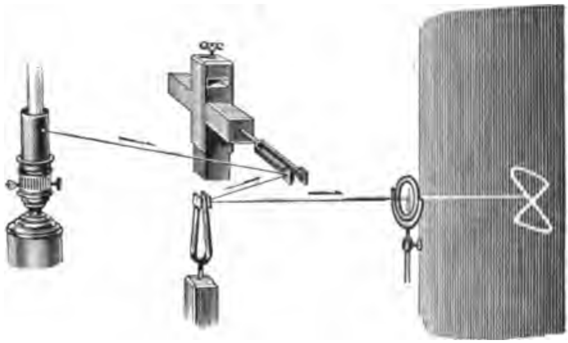

FIG. 32.—Apparatus for combining vibrations which take place in directions at right angles to each other.

one and thence to the other, we may graphically represent the combined motion (see Fig. 32). If the forks be so

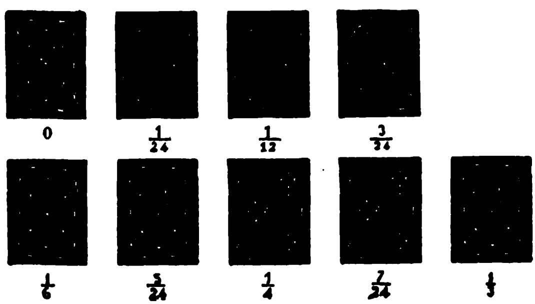

FIG 33.—Figures giving the projection upon a plane of the motion resulting from two vibrations which take place in planes perpendicular to each other.

placed that their planes of vibration intersect at right angles, the light image describes the complex curves which have become so well known as Lissajous's figures (see Fig. 33). These figures are determined in form wholly by the direction of the vibrations, by the relative amplitudes, and by the quickness of movement (the period). They furnish, however, *only the projection of the combined motion upon a single plane.* To represent the actual motion we should be compelled to use, not two, but three dimensions of space. This could be done by a laborious analysis of the motions, and by bending a wire to show for each instant the direction and the intensity of the combined motion. To further increase the complexity of the curves in the twisted wires it would only be necessary to set the tuning forks at some angle other than 90°.

iya's es.

Though no one appears to have had the patience, if he has had the desire, to produce such a scientific wire snarl as would set forth the motion combined from vibrating tuning forks, the late Professor Sekiya, of the

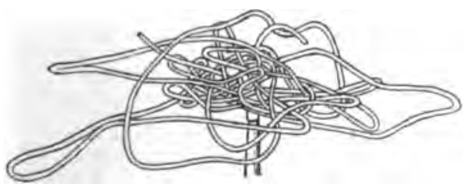

Fig. 34.—Wire model to show the nature of the registered motions (magnified) of a particle at a single observing station during the passage of shocks from the Japanese earthquake of January 15, 1887 (after Sekiya).

University of Tokyo, has analyzed the motions which reached his observing station during the Japanese earthquake of January 15, 1887. His results, which in three sections cover a minute of time, are known as "Se-

kiya's wires," and one of the sections is reproduced in Fig. 34.

Vorticose motion of objects.

The combination of shocks from separate faults, as we have seen, tends to bring about rotational movements in objects free to move at the surface of the earth. The plane of such rotational movements will here be the horizontal. Rotated columns of one sort or another have frequently been described in connection with earthquakes, and it is evident that they are not uniformly distributed within the area affected by the earthquake, but are found at certain favorable localities only. The classical example is furnished by obelisks in the façade of the Cloister of San Bruno in the town of San Stefano del Bosco, Calabria, which obelisks were twisted in three sections at the time of the earthquake of 1783 (see Fig. 35). Such vorticose motions were also especially characteristic of the Kingston earthquake of 1907, and in this case, as in the other, an adequate explanation is found in the fact that the city of San Stefano and the city of Kingston (see Plate XII) both lie at the intersection of prominent seismotectonic lines.

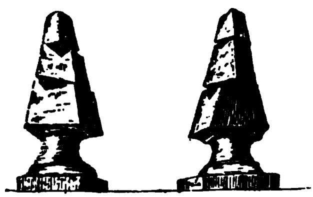

FIG. 35.—Obelisks twisted in three sections at the time of the earthquake of 1783 in Calabria.

Examples of vorticose movements in connection with earthquakes might easily be multiplied. We will mention but three additional instances. During the earthquake at Belluno on June 29, 1873, a bronze angel, which was pivoted at the summit of the dome of the cathedral, at a distance of two hundred and twenty feet above the ground, was turned through 20° upon its axis. The statue

had outspread wings, which were attached to the body by upwardly directed iron spikes ten feet in length. These wings were thrown to the ground so as to leave the spikes projecting out from the shoulders. An earthquake in the Rhine provinces, which occurred August 26, 1878, and was of sufficient strength only to throw down chimneys, was yet able to twist the statue of Minerva in the façade of the Royal Polytechnicum at Aix la Chapelle, in such a manner that its three component blocks were each moved upon the underlying base as were the blocks in the obelisks at San Stefano. The two outstretched arms of the statue were broken off and thrown down to the ground. During the Indian earthquake of 1897 many posts which were firmly set in the ground were so twisted as to produce spiral wrinkles in the ground surrounding them.

tional ations. The mechanical movements and the successional shocks which have been considered are clearly not the only ones which originate upon fault planes. Whenever the surface of one body slides upon that of another, waves are set up as a result of the friction between the surfaces. Such vibrations are of greater amplitude the greater the roughness of the surfaces involved, and the greater the pressure of the one surface upon the other. In the case of faults, the vibrations thus set up differ notably from the successional shocks already considered, and this by reason of their smaller amplitude (smaller intensity) and their shorter period.

Of the successional shocks which arise from vertical displacement upon a fault, we know that they are in most instances mainly upward and downward at the earth's surface, and that they appear to be propagated outward in all directions as a great wave or swell upon the surface of the ground. They are thus waves whose vibrations are

transverse to their direction of movement. Representing as they do a definite amount of energy, they are able to impart to the surface a greater amplitude, and hence cause greater destruction, wherever the outer layers are made up of loose or of lightly consolidated material.

Frictional vibrations have musical quality.

The secondary vibrations upon a fault plane which arise from friction are, by reason of their short period of vibration (the considerable number of vibrations per second), competent to produce a definite musical tone of low pitch. From the fact, also, that they originate entirely beneath the earth's surface, where the two sides of the fault remain in contact with each other, the resulting tone is subterranean. There is substantial agreement among observers that the sound phenomena heard in connection with earthquakes begin by a brief interval, a second or two at the most, before the shocks are felt.

Earthquake vibrations from a distance.

The "distant" study of earthquakes belongs to a subsequent chapter, but we may here anticipate enough to say that the two principal types of waves which reach distant stations from earthquake districts are (1) waves which have large amplitude and long period—the so-called "main waves"—and (2) waves of very small amplitude and of short period—the so-called "preliminary tremors." The amplitude of the large waves is from twenty to one hundred times that of the tremors, and their period is from ten to twenty times as great. The discovery made in 1907 that the larger waves certainly have their directions of vibration transverse to the line of propagation, leaves little doubt that they correspond to those which, in the neighborhood of the fault, we have called successional shocks, and which arise from the movements of the earth at the fault through the en-

tire distance of its displacement. In further corroboration of this conclusion is the fact that these large waves of the distant station are found to travel with a velocity only about one third that of the tremor, and this would account, also, for the fact that the subterranean rumbling sounds are so generally perceived before the sensible shocks reach the surface, even over the fault. The successional shocks can, in fact, hardly be conceived to begin until after the fault has fully opened. As already mentioned, these waves gain in length of period as they travel, and it is perhaps largely on this account that their capacity for destruction is lost in the vicinity of the fault. Their intensity (amplitude) is quite sufficient to still cause serious damage, were they only quicker in their movement of vibration.

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CHAPTER VI

THE LINES OF HEAVY EARTH SHOCK AND THE LINEAMENTS OF THE EARTH'S FACE

In the preceding chapters those earth faults have been discussed which become visible at the surface during earthquakes. The fact that measurable faults appear at the surface in connection with the grander earthquakes only, and not always even in such cases, when the mantle of unconsolidated rock material is relatively thick, raises the question whether any method has been discovered for locating deeply buried displacements, or those upon which small movements only have occurred.

The selective property of earthquakes. In certain notable earthquake countries, such as Calabria and Japan, it has long been recognized that all parts of the same province do not stand in the same danger from shocks. Each village has, so to speak, its own peculiar earthquake reputation; a reputation which is based upon the records of past earthquakes. To illustrate, the officials in the Central Bureau at Rome which is intrusted with the investigation of Italian earthquakes, would be considerably surprised to learn of damage which has been caused by earthquake shocks in certain of the Italian villages, whereas, from others a report is awaited whenever earthquakes are known to have visited the district. Certain of the Calabrian villages have re-

peatedly been wrecked by earthquake shocks, while others in their vicinity have remained immune.

It has been often pointed out, and especially by Austrian geologists, that the so-called epicenters of successive earthquakes within the same districts betray a tendency to recur at the same point or else to travel along a straight line. This fact has been particularly well brought out for the so-called Mürz line of Lower Austria (see p. 8, and Fig. 22), where the epicenters (points of heaviest shocks) have been repeatedly located at the same localities or have migrated in a single direction. The line of migration of the epicenters is here essentially rectilinear, has controlled the courses of streams, and as Professor Suess has shown, gives evidence from geological grounds that it is the course of a fault. A later example of the same kind of shock line has been furnished by earthquakes which have occurred in the vicinity of Chemakha, Turkestan, the epicenters of which are likewise ranged along a right line (see Fig. 9, p. 23).

From the statistical side the cause of the unequal distribution of earthquake shocks within a district has been carefully investigated. The data so assiduously and patiently gathered by Dr. de Montessus have furnished him an exceptional opportunity to study this problem. He has thus been able to show that in a broad way it is the vicinity of steep slopes that is characterized by the heaviest shocks. Of two contiguous districts, like the two sides of a valley, the two flanks of a mountain chain, or plains and neighboring heights, the more unstable is in each case that which presents the greatest average slope—the greatest surface relief, whether relative or absolute. He clearly recognized that this difference in favor of the steeper slope is undoubtedly to be explained

by the fact that steeper slopes are so generally above fissures in the crust upon which movement has occurred.

Seismic importance of river valleys.

It has often been shown that valley lines have been lines of seismic intensity, and here also the explanation is to be found in the fact that the streams which have carved out the valleys have been given their direction by a fissure in the crust now hidden beneath the valley deposits. The earthquake of

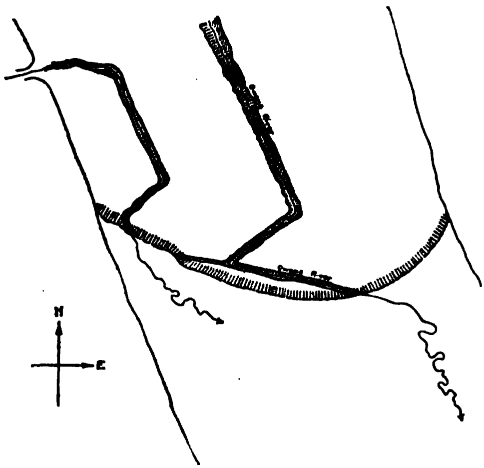

FIG. 36.—Sketch map to show the approximate course of the Owens River across lava floods in channels determined by fissures in the lava. Near Bishop, California (sketch by W. D. Johnson).

the Eastern Alps in the year 1882 was clearly localized along the sharp fracture valleys of that region. An earthquake which occurred November 4, 1877, was mainly felt along the St. Lawrence River, Lake Champlain, the Hudson River, and along the Mohawk and Connecticut valleys.

How the control of a river's course may be exercised by the fissures in the crust is well brought out by a sketch map of the Owens River near Bishop, California, which has been prepared by W. D. Johnson of the United States Geological Survey. In this vicinity the stream flows over a succession of lava floods hundreds of feet in thickness. The larger stream and a neighboring smaller one have each taken a zigzag course along fissures which penetrate the lava (see Fig. 36).

rthquakes d faulted tricts.

Not content with a study of the topography of earthquake districts and his discovery of the law of the steepest slope, De Montessus has examined the geological structure of each earthquake district, and shown that in far the larger number of instances the district is one where faults have been independently discovered in the examination of the geology. In those earthquake districts where faults have not been described, the districts have either been little studied or the rocks are of a nature which makes it extremely difficult to determine with certainty the presence of faults. The absence of well-determined dislocations within these districts does not seem, therefore, to offer a serious contradiction to the law otherwise found to apply, for in areas of crystalline rocks careful study may fail to disclose the position of faults actually known to be present.

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To represent with considerable detail the distribution of seismicity within an earthquake district Dr. de Montessus has devised a method of presenting the results of observation, which may be called the method of mapping habitual epicenters. The data for his purpose he has naturally found in terms of earthquake epicenters, and the shocks, whether heavy or light, few or frequent, he has, in a sense, measured up

and combined, so that by black circles of varying sizes the relative seismicity of the different portions of the district may be graphically set forth. In the sketch map of Scotland, represented in Fig. 37, we have an illustration of this method. For districts of many light shocks only, the method is especially well adapted, and furnishes quite trustworthy results. For those districts, however, which in historic times have been visited by a few destructive earthquakes only, the concentration of the shocks at one or more supposed epicenters fails to adequately represent the distribution of the seismic intensity. This limitation of the method, imposed by the form in which the available data are found, is fully realized by its author. Despite these limitations, the method seems to be a most important one for graphically representing the distribution of seismicity.

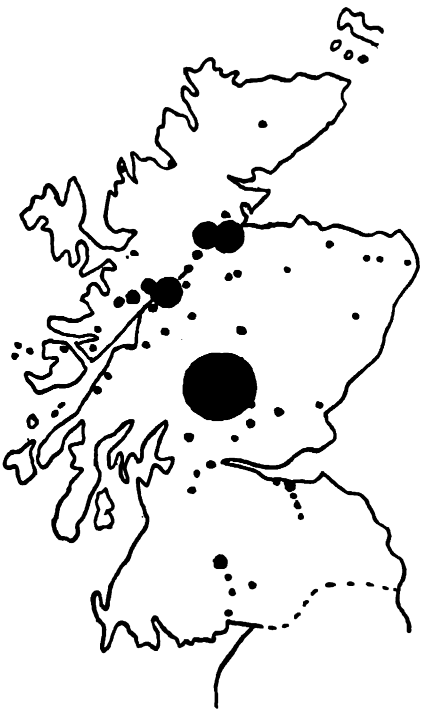

Fig. 37.—Sketch map of Scotland setting forth the distribution of epicenters and habitual epicenters (after De Montessus).

THE LINES OF HEAVY EARTH SHOCK

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The well-organized efforts on the part of the Italian Government to relieve the distress occasioned by the Calabrian earthquake of September 8, 1905, furnished unusually favorable opportunities for discovering the distribution of the destructive shocks within the Calabrian province. The district affected by the earthquake is one of overpopulation, and villages are well distributed over much of the territory. Into each village from which damage from the earthquake was reported a small body of troops was thrown, and a report quickly furnished upon the extent of the damage. These reports, after entry upon the large scale maneuver map at division headquarters, brought out the fact that damaged villages were ranged along the straight lines composing an intersecting network, and that villages located in the meshes of the network had remained relatively immune. The greatest damage was found to have occurred where the lines in the network crossed each other. The lines composing the network belonged to several parallel series, and many of them corresponded in position to buried faults already determined by geologists. Others were probably of this character, and this not alone because movement upon them had been indicated by the damage resulting, but, further, for the reason that they stood in a peculiar relation to the relief of the country. Such lines of excessive damage to structures upon the earth's surface, due to the intensity of the local shocks, with little doubt, therefore, revealed the position of buried faults, and hence may be designated *seismotectonic lines.*

It would appear that the surface of the earth is at the time of an earthquake in a measure sensitized to reveal the position of buried structures much as is the human body by a fluorescent screen, or in X-rays produced by some other

method. The seismotectonic lines are the projections upon the surface of the buried planes on which movement has occurred. It is well known that repeated movements have at the time of earthquakes occurred upon certain fault planes which are exposed at the surface. The long record of earthquakes within the Calabrian province suggested the application of a test to determine whether the seismotectonic lines revealed by the recent earthquake have also been the seat of earlier movements within the province. The test was applied through the preparation of maps to represent the distribution of damage in the province from each important earthquake upon record. The maps thus prepared show when compared that while certain of the seismotectonic lines have in nearly every instance been shaken, others have been shaken in exceptional cases only, when the district has been the scene of grander disturbances.

Repetition of heavy shocks along seismotectonic lines.

For purposes of study the lighter earthquake shocks are by far the more instructive, since the difficulty of grading the intensity of shocks when many places have been shaken is in such cases excluded. The mere fact that a village has felt an earthquake shock and its neighboring village has not, discloses the significant fact that it is nearer to the seat of movement. Such favorable villages for study, however undesirable they may be as dwelling sites, the study showed in most cases to be located at or near the intersecting points of seismotectonic lines. The simplest explanation for the seismic prominence of such intersections is the combination at these points of the movements upon all fissures which there intersect.

The consideration of other earthquake districts than the one in which the method was discovered, shows clearly that

the intersections of seismotectonic lines have repeatedly received the heaviest damage from earthquakes. The little island of Ischia, off the Bay of Naples, in Italy, is a volcanic island which has often been racked by earthquakes that have curiously been concentrated at Casamicciola. Though situated upon the flanks of an active volcano, no quick sympathetic relation has connected the eruptions of Monte Epomeo with the

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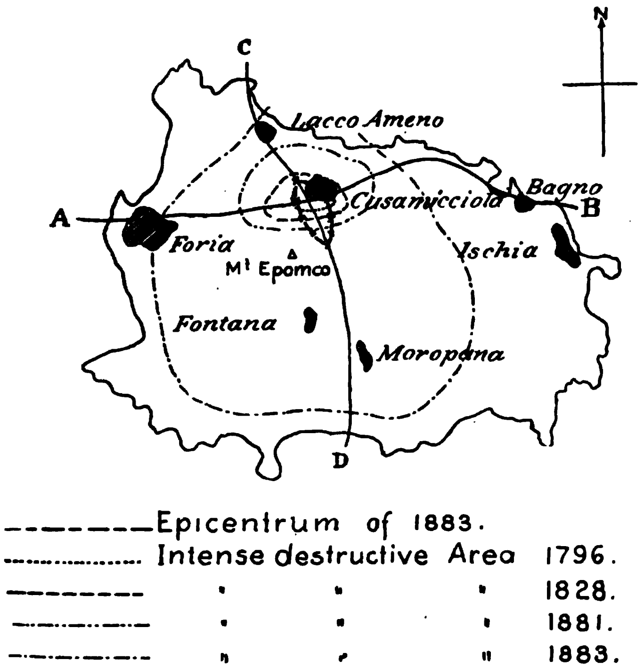

Fig. 38.—Sketch map of the island of Ischia to show the concentration of successive earthquakes at the city of Casamicciola. Earthquakes of 1796, 1828, 1881, and 1883 (after Baldacci and Mercalli).

local earthquakes. The shock of July 28, 1883, threw down every house save one in Casamicciola, and killed over two thousand people; yet delicate instruments in the Vesuvian Observatory, only twenty-four miles away, gave no indication of the disturbance. The shocks were felt, however, in towns which were ranged upon two lines crossing the island and intersecting beneath the city (see Fig. 38). These seismotectonic lines have been revealed as faults through the thermal springs and fumaroles ranged along them, and both springs and fumaroles showed unwonted vigor after the shocks had passed. The earlier earthquakes upon the island have betrayed the same tendency to strike with unparalleled severity at Casamicciola. The earthquake that occurred upon the evening of March 4, 1881, which destroyed one fourth of the houses of the city and killed 118 people, was accompanied by a marked twisting of pillars, but its destructive violence was limited to an area little more than a mile in width and two miles in length. The shocks were felt at Vivara along the continuation of the fissure *AB* (see Fig. 38) to the east and in Ventotene to the west, but nowhere upon the near-lying Italian shores.

Intersections of seismotectonic lines in Japan.

Davison's earthquake map of Japan for the years 1885 to 1892 (reproduced on page 47) reveals a number of small areas of relatively higher seismicity, which are at the intersections of prominent lines in the structure of the island. The islands composing the Japanese empire form a series of gigantic zigzags continued southwestward in the Loochoo Islands and northeastward in the Kuriles. The more noteworthy of the seismic areas is to be found at the great elbow of the main island, and the next most important one at the next great elbow to the southwestward, near the Straits of Ko-

rea. This is well brought out upon Kikuchi's more general earthquake map of Japan representing the shorter period 1885 to 1890 (*a*, Fig. 39). Additional centers of strongly localized but yet lower seismicity appear upon Davison's map, as is brought out in *b*, of Fig. 39.

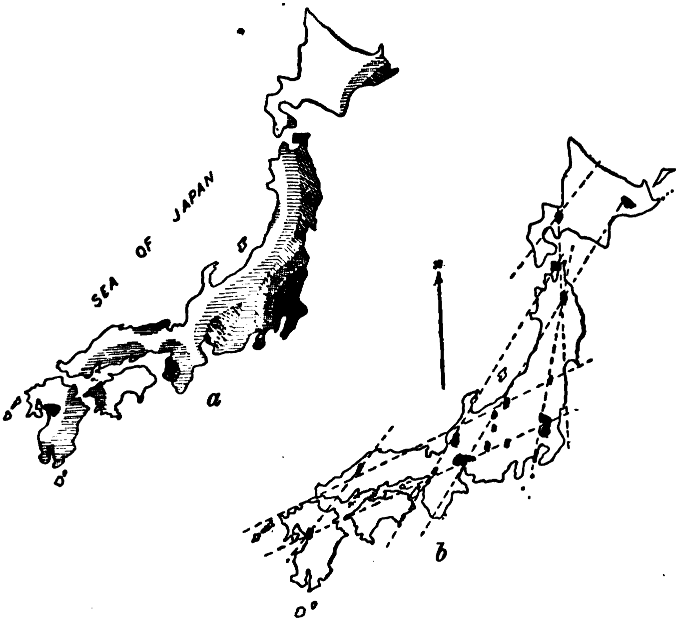

FIG. 39.—*a*, Kikuchi's earthquake map of Japan; *b*, seismotectonic map of Japan based upon Davison's map.

Seismotectonic lines of California. The records of earthquakes upon the Pacific coast have lately been assembled with some care, and the material thus collected has been utilized by De Montessus to compute by his method the distribution of seismicity for the province. He has not, however, made the attempt to actually locate the habitual epicenters

thus determined; and if we now supplement his studies by presenting the data upon the map, the seismotectonic lines come into prominence with the stronger earthquake centers at their intersections (see Fig. 40). The number of the lines thus indicated is relatively small, and the dominant directions are northwest-southeast (the direction of the more prominent of the known faults), and the nearly perpendicular direction, northeast-southwest. The data presented upon the map point clearly to an additional epicenter near Fort Klamath, Oregon; and the records show that on the morning of January 8, 1867, heavy shocks were felt there and were accompanied by important changes of level in Klamath Lake.

The greatest number of epicenters are ranged along the Santa Clara valley and its extension, the valley of the Russian River; but this unusual prominence may be in part explained on the same basis as the unusual seismic prominence of San Francisco, in the density of the population and the consequent fullness of the data.

The earth's surface as molded by erosion.

The casual observer of nature is apt to receive the impression that the straight line is absent from most landscapes, save only as detail is lost in the distant horizon. In the rounded profiles of hill and dale he sees ever the gently flowing curves of the Hogarthian line of beauty. The tendency of the erosional processes may truly be said to be to mold the surface so that it presents ever more softened outlines, until at last all bold and angular features have disappeared from the landscape. So, upon a slab of marble, the sharply chiseled characters of a significant inscription may, under the tooth of time, fade away into hardly perceptible grooves, which disappear beneath a growth of moss and ivy. Yet to one who will push aside the obscuring cover and dili-

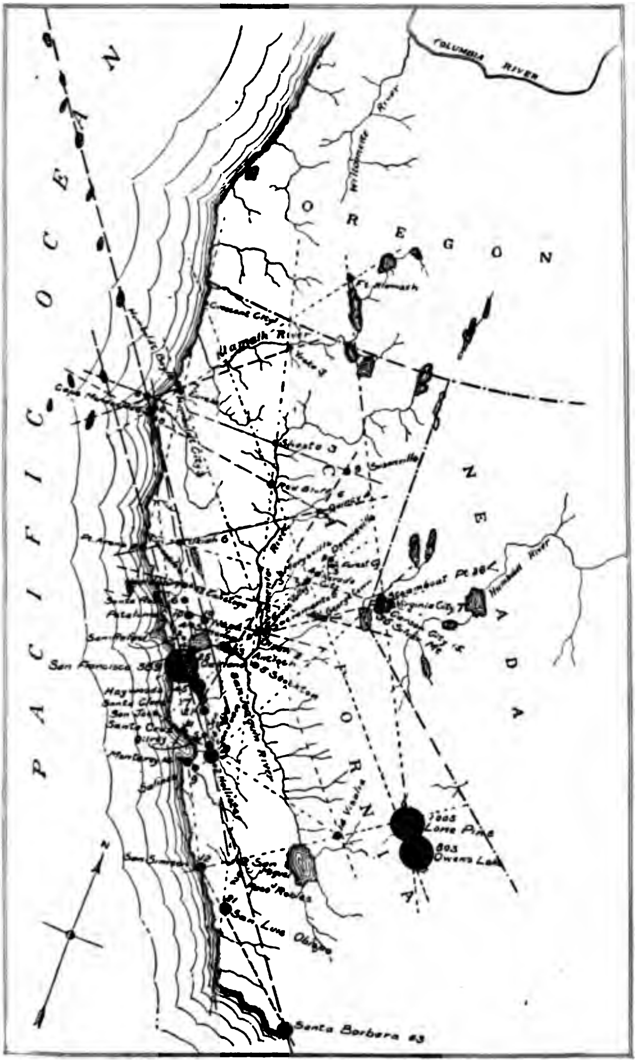

Fig. 40.—Map to show the habitual epicenters and the principal seismotectonic lines of California (epicenters computed by De Montessus). The elliptical spots within the oceanic area are the localities where shocks have been felt at sea.

gently devote himself to a study of the half-effaced inscription, the hidden secret may be revealed.

The lineaments of the earth's face. To the difficulty which the erosional processes impose upon the problem of discovering the earth's architecture, there are others which arise from the methods of representing the earth's surface upon maps. In thickly settled districts particularly, the significant lines of nature are lost in maps under the system of heavy black lines which show the course of the lines of commerce—the roads and railways. If, however, a map be prepared without these impertinent and confusing elements, it will generally be discovered that, though half concealed, the straight line is a number of times repeated upon the map. A rocky stretch of straight coast line is, it may be, extended landward in a low cliff, and this by a number of waterfalls aligned upon a number of streams. The straight line we have thus far followed is now continued by the beds of streams which have left their

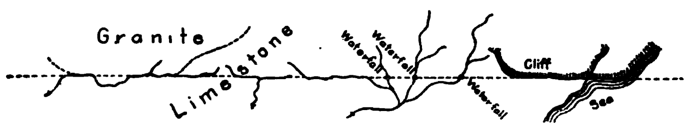

FIG. 41.—Diagram to show the composite nature of earth lineaments.

natural course under some mystical influence which does not at first appear. If, now, it is found that the rocks which outcrop at the surface of the ground belong to different types, it will perhaps be noticed that these types are for a considerable distance separated by a straight contact which forms the extension of the line with which we started from the shore. One or the other of these circumstances may be fortuitous, and hence misleading. The probability that all are thus accidental, and hence

without significance, is extremely small. Such a straight line drawn upon the earth's face has been termed a *lineament* (see Fig. 41), and is the revelation to us of the course of a buried fissure through the earth's crust, a fissure which in one place has formed a shore line, in another a cliff, again waterfalls and stream channels, or, finally, the contact of rock formations. Examples of such lineaments will be found upon the maps of Fig. 42 (p. 111) and Fig. 44 (p. 114).

[L]ineaments [m]ark the [co]urse of [fa]ults.

We may go a step farther and inquire how the several elements of the surface are connected with the fissure which passes beneath them. Fissure planes, generally vertical, are in most regions no rare phenomenon. Every quarry opened in rock reveals them, it may be, numbered by the hundreds or thousands. Belonging to a number of parallel series, these vertical fissures or joints divide the rock mass into closely packed prisms which appear as though built up from squared blocks of masonry (see Plate II, *A*). The lineament which we have described must, therefore, be a particular joint among the many with which we become familiar within the quarry. Sometimes we are able to show from the study of the rocks along its course that the ground has at some time been moved either up or down or laterally upon the one side, and not upon the other, or that the movement has at least been different for the two sides of the fissure. The fissure is thus determined to be a geological fault. At other times, when this cannot be proven, it is indicated as probable. At still other times the rocks upon either side of the fissure show no appreciable difference in position, and we are thus forced to conclude either that no movement has occurred, or if it has, that it has been compensated by a counter movement.

Composite nature of lineaments.

It is the composite nature of lineaments which explains why they have been so generally overlooked. It is not so much the fact that a cliff continues in a definite direction for a longer or shorter distance, as it is the persistence with which several elements in the surface all adhere to a definite straight line, in which the significance of the lineament consists. This changing character of the lineament is in part explained by the composite nature of faults themselves, for we know that the displacement along the fault line varies most abruptly and between the widest limits (see Plate II, *B*). This displacement may locally be reduced even to zero, and hence to the condition of a joint in some particular section of the line; or a reversal of movement may at some time reduce a former displacement to nothing. Thus the determination that beds lie at the same level upon opposite sides of a fissure does not in itself prove that movement has not occurred upon the plane.

Equivalence of lineaments and seismotectonic lines.

Lineaments thus appear, like seismotectonic lines, to reveal the courses of fault planes through the earth's crust. Their identity should, therefore, be revealed upon those maps which, in addition to the usual topographic and hydrographic data, set forth the distribution of seismicity. Such a map of the islands in the Greater Antilles may serve for illustration (see Fig. 42, p. 111). In this region the strong lineament which, starting from Jamaica, follows the straight southern shore of Haiti and the equally straight northern coast of Porto Rico to St. Thomas, is by far the most prominent of the seismotectonic lines. Less strongly indicated is the nearly parallel lineament which continues the southeastern coast of Cuba and its partially submerged extension to and along the northern coast of Haiti. Other lines are

only less clearly brought out by the earthquake records, and all are prominent lineaments. More significant yet is the fact that the habitual epicenters are so uniformly located at the intersections of the prominent lineaments.

The sharp fjords or firths of the northern British Isles bring the lineaments of that province into special prominence, even on outline maps. This region is, therefore, adapted to a comparison of seismotectonic lines with stronger lineaments.

The map of Fig. 43 reveals the seismotectonic lines and their identity with the important lineaments. The more important of the habitual epicenters are here also to be found at their intersections. The most important series of lines is directed east - northeast, and two of the four lines

FIG. 42.—Sketch map to show the identity of lineaments and seismotectonic lines for the Greater Antilles (seismic data after De Montessus).

represented in this series (AA' and BB') have been determined independently by geologists as faults. Likewise

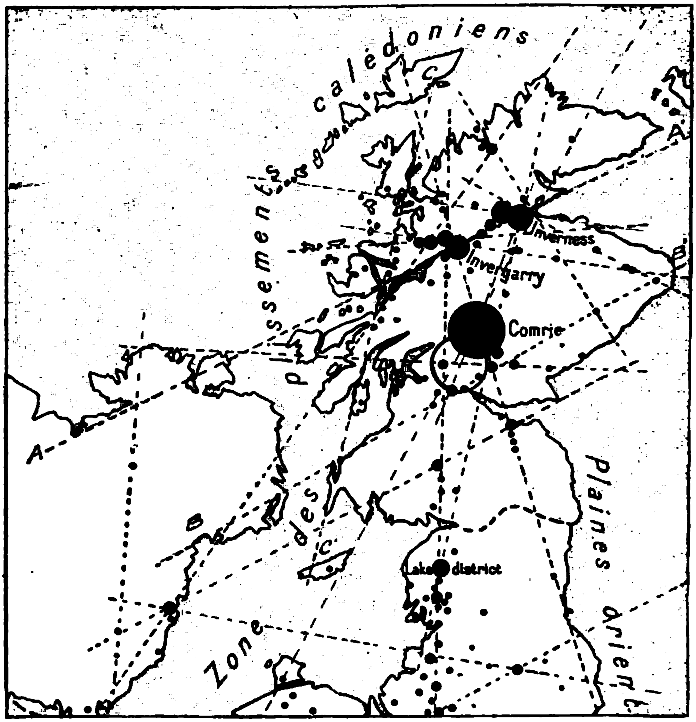

Fig. 43.—Seismotectonic map of the northern portion of the British Isles. The black circles are the habitual epicenters as computed by De Montessus, and the dashed lines the seismotectonic lines.

the line CC' directed to the east of north, is a well-known fault of the district.

Within that portion of the United States which borders upon the Atlantic, the correspondence of lineaments with

seismotectonic lines has been established. In this province the study of the lineaments was undertaken in 1904, before their relation to earthquake shocks had been suspected. The distribution of the seismicity throughout the province had, however, already been studied by De Montessus in 1898, and published in a generally inaccessible scientific journal at Geneva, Switzerland. So soon, now, as the two reports were compared in 1906, and the earthquake data transferred to the lineament map, it clearly developed that the habitual epicenters were located along the lineaments, with the epicenters of the higher grades at the important intersections (Fig. 44).

rthquakes l linea- nts in the tern ited tes.

Perhaps the most noteworthy of the coincidences brought out by this map appear in the cases of the northern fall line (*H*), the southern fall line (*I*), the Carolina coast line (*J*), the St. Lawrence line (*F*), and the Newark border line (Φ), the Connecticut and the lower Connecticut lines (*VI* and 1), and the St. Croix line (*I'*). All the above-mentioned lineaments, and to a less degree others as well, are marked out seismogenetically.

Upon the northern fall line are Washington, represented by six epicenters; Baltimore, represented by four; Philadelphia with seven; Burlington with two; Trenton with two; Princeton with one; Staten Island with one; New York with eight; Brooklyn with one; New Haven with three; East Haddam with one hundred and forty-five; Milford with one; Newton with one; and Boston with twenty-six epicenters. This long line of epicenters is also extended southwestward upon the continuation of the lineament along the base of the Appalachians. Without an exception, the larger circles which set forth the seismicity along this line correspond to intersections with

FIG. 44.—Combined lineament and seismotectonic map of the eastern United States (epicenters computed by De Montessus). Crosses over ocean locate seaquakes during Charleston earthquake.

other lineaments. The seismic importance of East Haddam, Connecticut, where the fall line intersects the straight lower stretch of the Connecticut River below Middletown, is very great, and the locality has first rank in seismicity for the entire region.

Nowhere is seismicity so localized within the region, excepting only East Haddam, as upon a line which joins Boston to Portland and is continued northeastward to Augusta and Fairfield in Maine. This line follows the straight coast line of central New England, but its real significance is first revealed when we examine the submerged contours of the ocean floor. The continuation of the line southwestward from New England, after passing the continental shelf, corresponds to the great escarpment at the border of that shelf—a cliff on which for more than 500 miles the ocean floor drops within the space of a few miles from depths of less than 1,000 to more than 9,000 feet. The position of this escarpment with reference to the neighboring continent is similar to that of the great Tuscarora scarp to Japan, and by far the greater number of Japanese earthquakes have been accompanied by movements along that cliff.

It will not have escaped the observation of the careful reader that seismotectonic lines or lineaments, in all the cases which we have considered, show a marked tendency to be grouped within a number of parallel series, just as do the joints in any region and the determined faults as well.

w of dis- bution of smicity.

The identification of lines of seismic activity with strong earth lineaments renders it necessary to reexamine De Montessus's laws of distribution of seismicity; for when examined in detail it is not always true of seismotectonic lines that they correspond to the

steeper slopes. Thus by far the most prominent seismic line of the eastern United States—the northern fall line—is for much of its extent, and here the more seismically active portion, hardly a line of relief at all. Much the same may be said of the two lines which stand next in importance—the Boston-Augusta line, and the St. Lawrence line. The first mentioned of these latter, *extended,* becomes the most remarkable escarpment either upon or near to the continent; and, similarly, the northern fall line, extended to the southwest of Washington, follows the base of the longest steep slope to be found within the land area under consideration. The law of steepest slope will therefore apply to portions of many, if not to the greater number of seismotectonic lines. In some way, however,—be it in the geologic contacts, in the arrangements of waterfalls, in lines of drainage, in coast lines, or in relief—all the seismotectonic lines are lineaments and presumably faults. De Montessus's law may, therefore, be expressed as follows:

Seismicity is localized on earth lineaments (faults), and is greatest at their intersections.

Lineament intersections and epicenters.

The intersections of the seismotectonic lines which correspond to the points of highest seismicity have, in the case of particular earthquakes, been generally determined as the epicenters of those disturbances, since epicenters are necessarily the localities of the heaviest shocks. Should new maps be prepared for each earthquake province, and for each earthquake which has been recorded within it, by locating each village which sustained damage, and designating by a numerical figure its seismicity for that particular disturbance, a composite map could be prepared by assembling the data from all the others, and this should afford results of the greatest

refinement and accuracy. It follows that such a method would be the most sensitive one yet known for discovering the fracture system present in the crust beneath the province.

The value of the methods which have now been discussed for determining the distribution of seismicity, must be measured with due consideration of their common attribute of revealing facts not disclosed by the methods in common use; which facts, therefore, might otherwise have remained undiscovered. As regards the provinces of low seismicity, one may have a deep interest in unraveling their tangled structures without the hardihood to invoke an earthquake in order to sensitize the province for one's purposes. There will, however, always be possible a scientific study of the scenery, which may be analyzed in terms of mountain and valley, cliff and plain, river and coast. In one of its sections a lineament may be represented by an escarpment, in another by a drainage line, in another by a fall line which intersects lines of drainage, in another by a geologic boundary, etc.; but the evidence of its presence is at hand and careful study only is necessary for its discovery.

e minor igzags f linea- ments.

The observation so often made upon the ground that the course of a line of dislocation is most frequently not straight, but made up of a great number of straight elements which, together, compose a series of zigzags, is indication that the lineaments which appear rectilinear upon the maps, may be so only in proportion as the scale of the map is small. Such lineaments must be conceived to outline, in the majority of instances, at least, a complex but comparatively narrow zone of smaller displacements in which other directions than the one given by the general trend of the dislocation are rep-

resented (see Fig. 45). The principal dislocation, while making excursions in zigzags to either side of its general course, does not, however, in the majority of instances, deviate very far from this average course. Such lines, if the projection of approximately plane surfaces upon

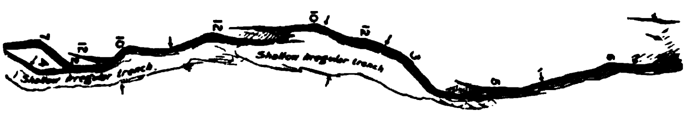

FIG. 45.—Map of some of the fault scarps which appeared in the Owens valley, California, during the earthquake of 1872. Surveyed by W. D. Johnson, United States Geological Survey, in June, 1907. Scale: 1 inch equals 430 feet.

the surface of the earth should, upon the common form of maps, appear as curves—as the projections of great circles. This necessary correction in their delineation, like the influence of erosion in everywhere molding curving outlines, has often most effectively obscured these significant lines of the landscape. For these reasons they are so little likely to force themselves upon the attention that the key to their system will have to be diligently sought out.

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CHAPTER VII

DERANGEMENT OF THE SURFACE AND UNDERFLOW OF WATER

A neglected phase of earthquake study.

THE theory of earthquakes which was probably propounded by Thales nearly six centuries before the Christian era, the earliest theory that has been preserved, was framed to account for the remarkable changes in the underground flow of water at the time of earthquakes. From the same early period, scenes familiar to the wandering Israelites are reflected by the Psalmist when he writes: "Tremble, thou earth, at the presence of the Lord . . . which turned the rock into a standing water, the flint into a fountain of water." From accounts by Aristobulus, the ancient geographer Strabo has handed down to us the record of an earthquake in India which, through the shifting of river channels, destroyed no less than a thousand villages. Yet from the days of Thales to our own no theory of earthquakes has been framed which has stimulated observation of the derangement of water-flow by earthquakes, either at or below the earth's surface. It is safe to say that no phenomena which accompany earthquakes, save only the shocks themselves, are so constant in their occurrence as the derangements of water-flow.

For convenience of consideration, it is well to separate the derangements of surface waters, those which either

stand upon or flow along the earth's surface, from those which are concerned with changes in the underflow, as manifested especially by a transfer of water either to the surface from below, or from the surface downward into the ground. Derangements of the first class, then, are chiefly concerned with a lateral movement *upon the ground*, while those of the second class relate to an essentially vertical movement *beneath the ground*.

sifica- n of the nomena.

Either directly or indirectly, the more important derangements in the flow of water, whether they be above or below the ground, are occasioned through differential changes of level of the ground itself. Thus new depressions or basins appear upon the surface. In the greater number of instances these depressions do

mation basins.

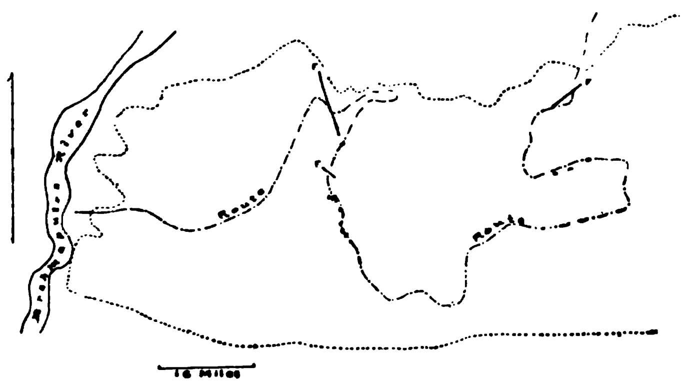

FIG. 46.—Sketch map to show the route followed through the country most disturbed during the shocks in India on June 12, 1897. The heavy lines are the courses of faults, and the black spots are the larger lakes (after R. D. Oldham).

not reveal the bed rock at the surface, and are not bounded by visible faults. No less than thirty earthquake lakes were observed after the great Indian earthquake of 1897,

and from the small part of the disturbed country which was examined, these could have been but a small proportion of the total number formed at the time (see Fig. 46). One of the new lakes dating from this earthquake was a mile and a half across. In the "sunk country" formed along the lower Mississippi during the heavy earthquake shocks of 1811–12, many new lakes came into existence. One of these, known as Reelfoot Lake (see Plate XV, *A*), is more than twenty miles long, and on it the fisherman in his canoe may pass over the tops of submerged forest trees.

In steep-walled mountain valleys heavy earth shocks nearly always occasion landslips, and these may completely block the course of a river. The lake formed in this manner during the great earthquake of January 25, 1348, in the valley of the Gail, Carinthia, destroyed no less than seventeen villages, and to-day, nearly six centuries after the occurrence, the area is a great marsh. Vivenzio counted fifty lakes of this character after the great Calabrian earthquake. The numberless circular openings in the ground formed during earthquakes (see below) are often left filled with water, thus dotting the landscape with a myriad of small pools. After the great Calabrian earthquake of 1783 numberless pools of this kind were seen, besides two hundred and fifteen lakes of larger dimensions. The greater number of earthquake lakes result from obstructions raised in the course of rivers through differential adjustment of earth blocks. Many such lakes were formed during the Sonora earthquake of 1887, and others during the earthquake in the Owens valley of March 26, 1872 (see Plate XVI, *A*).

The areas of former lakes may be very greatly extended by an earthquake, as was the case during the heavy shocks in

the region about the southern end of Lake Baikal on January 12, 1862. Here a strip of country 21 kilometers in length, and with a breadth which varied from 9.5 to 15 kilometers, suddenly sank and was soon after invaded by the waters of the lake.

ages in courses streams.

The derangements of stream flow during and succeeding earthquake shocks may be either temporary or permanent. In the first category belongs the rolling up of great waves upon the surface, and also the sudden reversal of the direction of current. During some of the first heavy shocks of the New Madrid earthquake of 1811–12, the current of the Mississippi River flowed northward, or opposite to its usual direction, for a period measured in minutes. At about the same time a great wave was formed upon the surface, which, rolling in upon the shore, snapped off large trees like pipestems, and swept boats far inland. During the Owens valley, California, earthquake of 1872, the Owens River near Lone Pine, a stream deep and swift and between 60 and 80 feet wide, was left dry for several hours. During the earthquake of January 25, 1348, the Grand Canal in the city of Venice was left dry.

The vastly increased volume of the water which comes to the surface during an earthquake generally causes a temporary increase in the flow of rivers within the district. In some instances they have at these times advanced with a high wall of water like that formed from the bursting of a dam.

Permanent changes to stream channels are most frequently observed within the level delta regions of great rivers, where the shifting of the channels of the numerous distributaries causes untold damage in the populous district about and between them. Such changes are, how-

ever, not always restricted to delta regions. During the California earthquake of 1857, the current of the Kern River was turned up stream, and the San Gabriel River left its bed to follow a new course determined by an earthquake fissure.

Waterfalls and pools. The fact has already been noted that earthquakes betray a marked tendency to be localized along river valleys, due to the fact that the valleys themselves have been carved out by erosive processes along the courses of ancient faults. When, now, new movements recur along these faults, to the accompaniment of earthquake shocks, the fault plane, before hidden under alluvial deposits, may be revealed as a wall or scarp which follows the direction of the valley bottom. Wherever this scarp intersects the windings of the stream in such a manner that it faces the downstream direction, the water of the river must fall over it in a cascade. In those places, however, where the scarp intersects the stream so as to face upstream, it dams the water and forms a pool. These changes were many times illustrated along the course of the Chedrang River after the earthquake in India on June 12, 1897 (see Fig. 60, p. 163).

Draining of lakes and swamps. In connection with the Japanese earthquake of 1891, a former lake was intersected by the course of the principal fault, and was by it cut in half, so that that portion of the lake which was over the raised limb of the fault was laid dry. By this uplift the former outlet of the lake was closed, and though the water still continued to enter the lake from a small stream, the level of its surface did not rise, owing to the fact that the excess of water drained away along the fault line. Near Flagstaff, Arizona, there is an old earthquake crack along which the waters of several rivers which intersect it all

A. One of Several Streams which Disappear where They Meet an Earthquake Crack near Flagstaff, Arizona. (After a photograph by A. E. Hackett.)

B. Sandstone Pipes in Limestone on the Coast at East Anglesey, Wales. (After a photograph by Edward Greenly.)

disappear down the crevice (see Plate VIII, *A*). The most remarkable revelation of the process of lake draining during earthquake shocks has been furnished by the former Lake Eulalie, which was situated near New Madrid, Mississippi, and which was completely drained at the time of the shocks of January 6, 1812. Upon the lake bottom thus exposed there was revealed a series of parallel fissures with funnel-shaped openings ranged along them (compare Plates XIII, *B* and XVI, *B*).

w springs d change volume of ones.

It is the commonest of observations that springs appear after an earthquake in places where before none had existed, and that many old springs either increase their volume, decrease it, or dry up completely. Such changes are the more marked and sudden for those springs which in their flow show least sympathy with the local rainfall, and which, moreover, have a nearly constant temperature throughout the year. They thus betray the fact that the water which flows from them rises from a considerable depth, where the supply is but little affected by the local rainfall, and the temperature only slightly modified either by the summer's heat or the winter's cold. Even more noteworthy are the changes which, at the time of earthquakes, are observed in thermal and mineral springs rising from still greater depths below the surface. All such deep and constant temperature springs are located along fissures in the earth's crust, as is clearly revealed by their alignment upon it. Probably in the vast majority of instances they are also located at fissure intersections, where the widening of the crevice has produced a natural shaft similar in character to the artificial one of an artesian well. The water from all such springs is derived from a saturated zone, separated from the surface by an impervious layer which is perforated by the widened

crevices below the points where the springs appear at the surface. In Fig. 47 this fact is brought out for the springs of the vicinity of South Britain, Connecticut, where the fissures are well-determined faults.

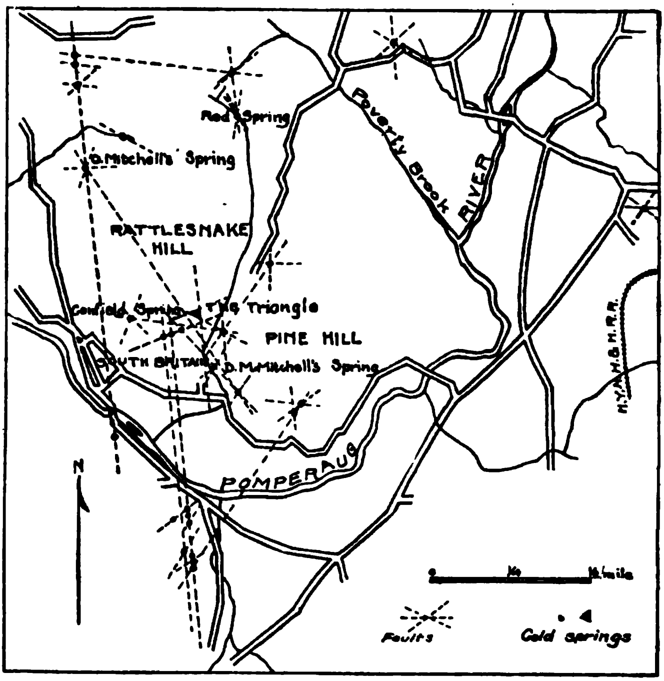

FIG. 47.—Relation of springs to fault intersections in the vicinity of South Britain, Conn.

The common "surface" springs vary both in volume and in temperature with the progress of the season, and are located where the surface of the saturated soil, the water-table, comes out to the surface of the ground. The position of this water-table within the ground is revealed

to us by the level to which water rises in ordinary wells. During an earthquake the water-table migrates, in some places upward and in others downward, and causes great changes in the behavior of wells. With the advent of shocks wells have frequently been observed to fill with water and flow over at the surface, generally roily or even choked with large quantities of sand and mud. After flowing in this manner for a brief period, they may quite as suddenly be emptied and cease altogether to flow.

avior of rmal ings. The changed volume of fissure springs induced by sudden earth movements may be illustrated by the action of some well-known thermal springs. After one of the heavy earthquake shocks in 427–6 B.C., the warm springs of Thermopylæ and Ædepsus did not flow for three days. After the earthquake of April 27, 1894, the springs of Thermopylæ remained unchanged, though those of Ædepsus were immediately so increased in volume that they produced turbulent and steaming brooks. Due to its increased flow, the little spring, Therma, at Gialtra, formed a funnel in the earth of 150 cubic meters capacity (about 196 cubic yards). At the time of the great Lisbon earthquake of November 1, 1755, the effect upon springs was noted far beyond the limit of the sensible shocks. The hot springs of Teplitz, Bohemia, suddenly became roily, next stopped flowing completely, and then broke out colored red with iron oxide, and flowed with such volume that all the bath basins were overflowed and considerable portions of the city inundated. Other springs in the same general region showed, however, no change. Recent studies made in Japan seem to indicate that even during light earthquakes the pressure of the water in artesian wells is influenced so as to be either greater or less than the normal.

Earthquake fountains and geysers. Not only does underground water issue from the surface in new springs which are born in the moment of earthquake shocks, but the water is sometimes projected upward from openings in the surface with such violence as to produce earthquake fountains resembling geysers, save only for their more continuous performance. During the New Madrid earthquakes of 1811 and 1812 water was projected upward in vertical sheets over the entire area of open fissures, and carried to the tops of the highest trees. When the earthquakes were felt at Aquila in central Italy in the years 1702 and 1703, the ground near the city was seen to open, and water and stones were ejected in such quantity that the surrounding fields became impassable. The columns of water are reported to have exceeded in height the tops of the highest trees. Likewise, during the great earthquake in India in 1897, the ground was seen to open at many points, and fountains variously estimated in height shot upward from the ground and flowed continuously for a considerable period. The Charleston earthquake of 1886 occurred during the night, but the unmistakable evidences of such fountains as we have described were left behind in great openings in the ground above which the leaves of the trees were incased in sand.

When in the vicinity of Lake Baikal during the earthquake of January 25, 1862, the surface of the steppe was suddenly dropped over an area of 250 square kilometers; fountains opened at many points within the sunken area, and water shot up to heights of 6.4 meters, or 20 feet. The water gushed also in great volume from the open wells, and where these were tightly covered by wooden caps the latter were shot into the air like the corks from champagne bottles. On the night of Sep-

A Craterlet which was Formed during the Earthquake in California on April 18, 1906.
(After a photograph by Branner.)

tember 5, 1896, during heavy earthquake shocks in Iceland, a new warm spring suddenly opened to the accompaniment of loud roaring and whistling, and threw water, steam, and fragments of rock to a height estimated at 600 feet. Its force was, however, soon spent, and a few hours later it played to a height of 10 or 12 feet only. Ten days later it had ceased to flow. Nearly all the geysers within the Iceland district suffered changes at the time of this earthquake, and the famous *Strokkur*, which had been born during the earthquake of 1789, suddenly ceased erupting, and came to an end. Mount Hecla and the other neighboring volcanoes remained perfectly quiet during this earthquake, and were obviously in no direct way connected with it.

unnel-haped penings ned with nd—aterlets.

It seldom happens that the water reaches the surface of the ground with such violence as has been described without bringing along with it great volumes of sand or clay. It is thus in a position to leave a record of its behavior, and these records are of very considerable interest to the student of seismology. In character the transported material is most frequently sand of a different nature from that which before surrounded the site of the opening. The presence of mica scales and of other light bodies scattered through the sand—and these are rather characteristic ingredients—is accounted for by the fact that such materials are easily picked out from sands of composite character, and easily carried along by the ascending current. The volume of the water and sand which are discharged at the time of an earthquake has in many cases been sufficient to blanket large tracts of the surrounding country with quicksand. This has been especially true of the earthquakes of Calabria in 1783, of New Madrid in 1811, of India in 1897, and of Formosa in 1906 (see Plate XV, *B*). The openings from which the

water and sand have gushed are usually left in the form of circular funnels in the ground, and these have been termed "craterlets" (see Plate IX). Such sand vents seem to have been first described scientifically in connection with the report upon the earthquake in Calabria in 1783 (see Fig. 28, p. 80). Sometimes filled with water and surrounded by radial cracks, at other times these hollows showed only a lining of sand. By digging down beneath

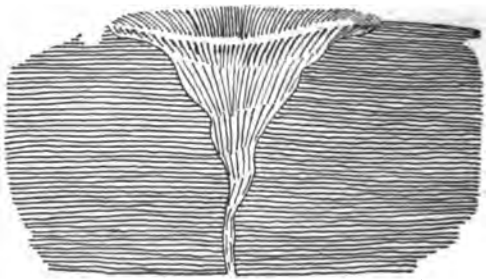

FIG. 48.—Section of one of the circular openings formed in the plain of Rosarno during the Calabrian earthquake of 1783 (after Lyell).

them it was found that they had the form of trumpet-shaped pipes standing erect, and that the loose micaceous sand in the center marked the course of the tube up which the water had ascended (see Fig. 48). These hollows were, moreover, found to be arranged along the course of fissure lines. Illustrations of such alignment in the case of more recent earthquakes will be found upon Plate XIII, *B*, and Plate XVI, *B*. The craterlets formed during the earthquake in India, 1897, were generally six feet or more across (Plate X), while those of the Charleston earthquake of 1896 had sometimes a diameter of as much as twenty feet. The groups of craterlets formed in connection with this earthquake were arranged in zones which

PLATE X.

Sand Vents at Rowmari. Formed during the earthquake in India on June 12, 1897. (After R. D. Oldham.)

Fig. 49.—Map of the principal areas of craterlets formed during the Charleston earthquake of August 31, 1886. The dashed lines are seismotectonic lines, and the black spots on the railway track the points where special damage occurred.

appear to correspond to the course of buried fissures, for their extensions are found to intersect the railway tracks at points of maximum damage. Other areas of the craterlets are found where such lines extended intersect each other (see Fig. 49). There is ample evidence that the craterlets serve not only as shafts to bring the water to the surface, but in many cases also for a subsequent drawing down of the water which has already been poured out. Examples of this were furnished by the Belluno earthquake of 1873, the New Madrid earthquake of 1811, and by the Achaia earthquake of 1861.

Sand cones with craters.

The sand ejected from openings in the ground during shocks of earthquake is not in all cases left in the form of circular hollows, but is often heaped up into cones which are surmounted by craterlike depressions. Thus, during the New Madrid earthquake of 1811 such cones formed distinct topographic features which are even to-day, though flattened by the wash of many rains, easily recognized. They stand out the more prominently because the white micaceous sand of which they are built up differs from the subjacent material, and has not a sufficient admixture of other ingredients to support vegetation. Such cones have to-day diameters varying from twenty to one hundred feet, and heights of from three to four feet.

The sand cones which were formed along the Mediterranean coast of Achaia during the earthquake of December 26, 1861, are of more than usual interest, for the reason that they were studied by a competent geologist almost immediately after their formation. These sand cones were built up over ground which was steadily sinking, and where many fissures intersected to form radiating "stars" of cracks, such as are well known from the Calabrian earth-

quake of 1783 (see Fig. 28, p. 80). It was particularly observed that the sand cones were here built up over the ganglia of radiating fissures, and they were numbered by

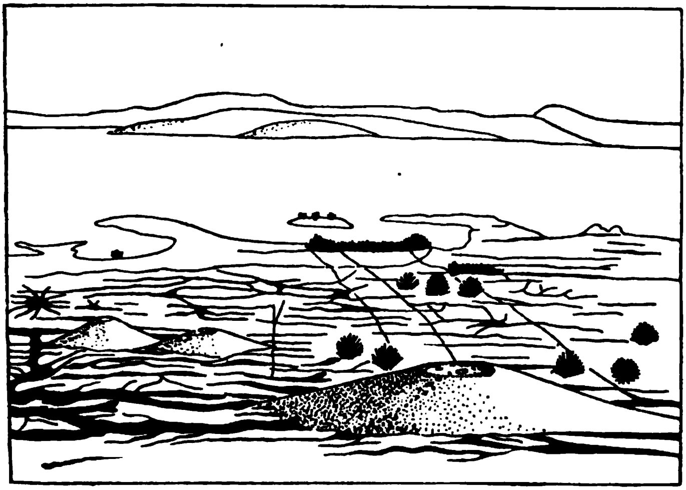

FIG. 50.—Sand cones formed on sinking ground in Achaia during the earthquake of December 26, 1861 (after J. Schmidt).

the hundreds upon the flat surface of the plain. Some of the largest had a diameter at the base of as much as sixty-five feet, but their craters were hardly more than a yard in diameter (see Fig. 50).

In connection with the same earthquake some extremely small cones were actually seen in process of formation as the ground was still sinking. In these instances, hydrogen sulphide gas, so generally emitted from the surface of the ground during earthquakes, escaped with the water at the crater of each little mound, in the form of a bursting bubble which scattered the fine sand upon the slopes.

It is little likely that the bubbles of gas play any important rôle in the formation of the larger cones, and whether a craterlet or a sand cone will develop at any point is likely to be largely determined by the violence of the ejection. There is here a distinct parallel with the form of volcanic cinder cones, since the larger and broader craters can be ascribed to more explosive eruptions, and the high cones with small craters to eruptions of less violence long continued.

Mud cones and mud volcanoes. During the heavy shocks of earthquake felt near Chemakha, Turkestan, on February 12, 1902, salty, plastic mud exuded from the open faults and built up high hillocks of the pasty material, which were surmounted by craters (see Fig. 51). Subsequent shocks were accompanied by movements upon the same fault planes, which fractured the cones already built up so as to form vertical walls on which a new displacement, amounting in some instances to 1.5 meters (about 1.66 yards) was measured. Many so-called mud volcanoes differ in no essential particular from these earthquake mud cones, and in fact the arrangement of mud volcanoes in line, and the connection of the episodes of their life histories with earthquakes in their vicinity, place them in the category of earthquake phenomena.

FIG. 51.—One of the mud cones formed during the earthquake of Chemakha, Turkestan, on August 22, 1902 (after Weber).

We have seen how the fissures, or those portions of them through which the underground water ascends to the surface during the earthquake, are generally left choked

uvenirs prehis- ric earth- akes.

with sand. The excavations which were made after the great Calabrian earthquake disclosed beneath the circular hollows a trumpet-shaped pipe, filled with sand, which descended straight downward into the ground. In the "sunk country" of the Lower Mississippi, which was formed at the time of the great

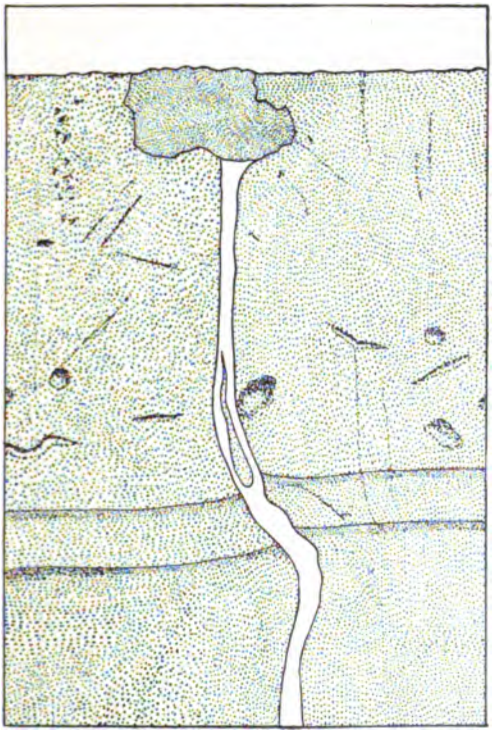

FIG. 52.—Earthquake fissure choked with sand left by the earthquake of the Lower Mississippi valley in 1811 (after a photograph by Thomas Beckwith). The white band is the micaceous sand which was left to choke the fissure.

earthquake of 1811, entire fissures were filled with the peculiar micaceous sand which welled out to blanket the

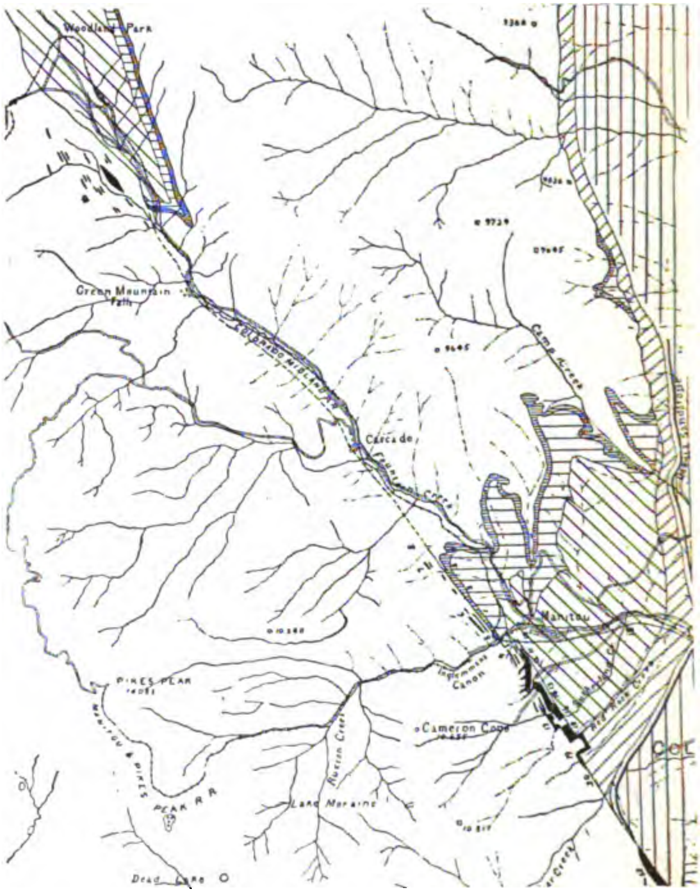

FIG. 53.—Sandstone dikes along the course of the great fault of Ute Pass, Colorado (after Crosby). The black areas are the sandstone dikes.

country, and these fissures may still be seen where the ground has been opened on vertical cliffs (see Fig. 52).

In favorable localities such sand-filled fissures as have just been described have been preserved for us from earlier geological periods, though with the sand now hardened into sandstone. Such sandstone dikes reveal to us something of the earthquake history of ages long since past. Thus, for example, in northern California, there are many vertical cracks filled in with a micaceous sand rock which has formed out of sand that has come upward toward the surface from below (see Plate XI). Near Colorado Springs, in the State of Colorado, somewhat similar dikes of sandstone have been left, the principal one of which takes a sometimes zigzagging course along an ancient lineament for a number of miles, to be represented farther to the northwest by a considerable number of smaller and parallel dikes of sandstone (see Fig. 53).

Sandstone pipes.

Of the smaller craterlets and sand pipes of a former geological period, there appear to be remains upon the eastern coast of Anglesey in Wales. A section of one of these is represented in Fig. 54, and a view of a number of such craterlets which, since their induration into sandstone, have been hollowed out by glacial action, is given in Plate VIII, *B*. These plugs of sandstone have the same trumpet form as

FIG. 54.—Section of one of the sandstone pipes in limestone on the eastern coast of Anglesey in Wales (after Greenly). α cherty limestone, β sandstone pipe, γ cherty limestone.

the sand below the Calabrian craterlets, and they are continuous above, with a spreading blanket of the same sand. They occur in a cherty limestone, are covered by the same, and may have been formed upon the sea floor.

Probable cause of the derangements in waterflow.

All the derangements in the underflow of water at the time of earthquakes are susceptible of a simple explanation through the differential changes of level of the blocks within the earth's crust. The most significant of the observed facts are that, in different portions of the district affected by a single earthquake, conditions have been absolutely different. Whereas in one portion all surface water before present in ponds and swamps has been sucked down into the ground, at the same moment, and only a few miles away, water has been issuing from the ground in great volumes, either along the course of fissures or through openings ranged on fissure lines. Consideration of all well-described regions shows, moreover, that where the water has issued from the ground in quantity, there the ground has been suddenly depressed during the shocks. The earthquake fountains, therefore, and the openings from which they discharge—the craterlets—are the loci of ephemeral and greatly overgrown fissure springs which the movements causing the earthquake have brought into existence. The drained bed of Lake Eulalie, after the shocks of 1811 in the Lower Mississippi valley, showed that in this instance the water had been sucked down through the openings on fissure lines. With these facts in mind, we may consider the direct result of adjustments which take place between adjacent blocks of the earth's crust everywhere intersected by vertical fissures and containing porous layers saturated with the underground water (see Fig. 55).

Whenever a block of the crust has been suddenly

PLATE XI.

GREAT SANDSTONE DIKE IN SOFT SHALES ON THE ROARING RIVER IN NORTHERN CALIFORNIA. (After Diller.)

dropped, the tendency has been to squeeze out through the fissures to the surface the water in the aquifers or water layers. Whenever the reverse movement has occurred, the inertia of the rock mass has tended to produce a subterranean vacuum, and in consequence to suck down through the fissures all the available surface water. The after shocks of great earthquakes seem to be largely

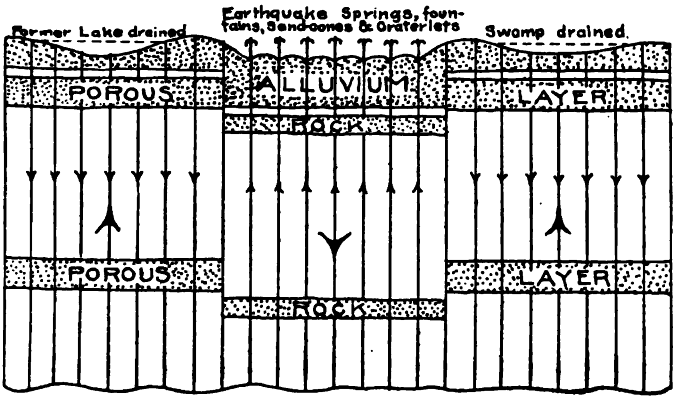

FIG. 55.—Diagram to illustrate the derangements brought about in the underflow of water by the movements which produce earthquakes. The heavy arrows show the direction of movement of the blocks, and the smaller arrows the course of the water within the joint planes.

brought about by later adjustments among the earth blocks, and doubtless account for the later sudden changes, either in the amount or the direction of the waterflow, which have been so often described.

There are other results of the adjustment of the earth blocks which must modify the effects just described, though their importance is probably of a secondary order. Recent earthquake study has shown that lateral compression

or expansion of individual portions of the earth's surface is one of the consequences of the earth movements which produce earthquakes. Expansion must operate largely through the widening of joint crevices, while compression will bring about their closing. The former should induce a tendency to draw down surface water, and the latter to squeeze out the ground water.

As regards the behavior of wells, this is perhaps more often to be accounted for through changes brought about in the level of the water table, which in turn is dependent upon changes of level of the earth's surface itself.

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CHAPTER VIII

SOME GREAT EARTHQUAKES DESCRIBED

THE lower valley of the Tagus, upon whose bank the city of Lisbon is built, has a long record of disastrous earthquakes, the most noteworthy of which have been those of 1309, 1531, and 1755. This quality of the Tagus valley does not end at its mouth, for the sea off shore is matched by but two other areas of sea bottom in its long list of seaquakes which have been perceived on shipboard. An explanation for the peculiar instability of Portugal may be found in its geological structure. The land area included between the lower Tagus and the sea represents a block of the earth's crust bounded upon the northeast by the great escarpment which, to the southward from the mouth of the Duero, continues the coast line of the Iberian peninsula. Against this scarp the massive crystalline rocks which compose the area to the eastward are suddenly cut off at the abrupt terminations of the Serra da Estrella, the Serra de Carcunello, and the Serra Gralieira. At the foot of this scarp other and later geological formations are found.

Only less striking as a geological boundary is the lower Tagus itself, whose direction is continued across the peninsula to Santander as a notable lineament that is followed by the Duero and other rivers, and by the Serra da Es-

trella particularly. To the southwestward of Lisbon, this line is continued beneath the sea as an important submerged escarpment, while to the northward of the Iberian peninsula its extension intersects the Bilbao cable at or near to the point where it has been periodically fractured. The escarpment which continues the northwestern Iberian coast line to the sharp bend of the Tagus, and separates the older crystalline formations from the newer deposits at its base, continues generally as a geological boundary to the mouth of the Guadiana River. The position of these lineaments, and the blocks into which they divide the peninsula, are shown upon Fig. 56.

great on hquake 755.

Among the earth movements which in historic time have affected the kingdom of Portugal, that of November 1, 1755, takes first rank, as it does, also, in some respects, among all recorded earthquakes. The first shocks of this earthquake came without other warning than a deep sound resembling thunder, which appeared to proceed from beneath the ground, and it was immediately followed by a quaking which threw down almost the entire city. In six minutes 60,000 people perished. The day was almost immediately turned into night, owing to the thickness of the dust from the shaken city, but quickly took fire, so that to the destruction from the shocks was added the horrors of a conflagration and a pillage by robbers. The direction of the earth shocks upon this day, as in so many other Lisbon earthquakes, was from the southwest to the northeast, or parallel to the valley of the lower Tagus. Portions of the seacoast between Cape da Roca and Cape Carvoeiro fell away into the sea, and damage was extreme along the coast between Cape St. Vincent and the mouth of the Guadiana. The great Serra da Estrella,

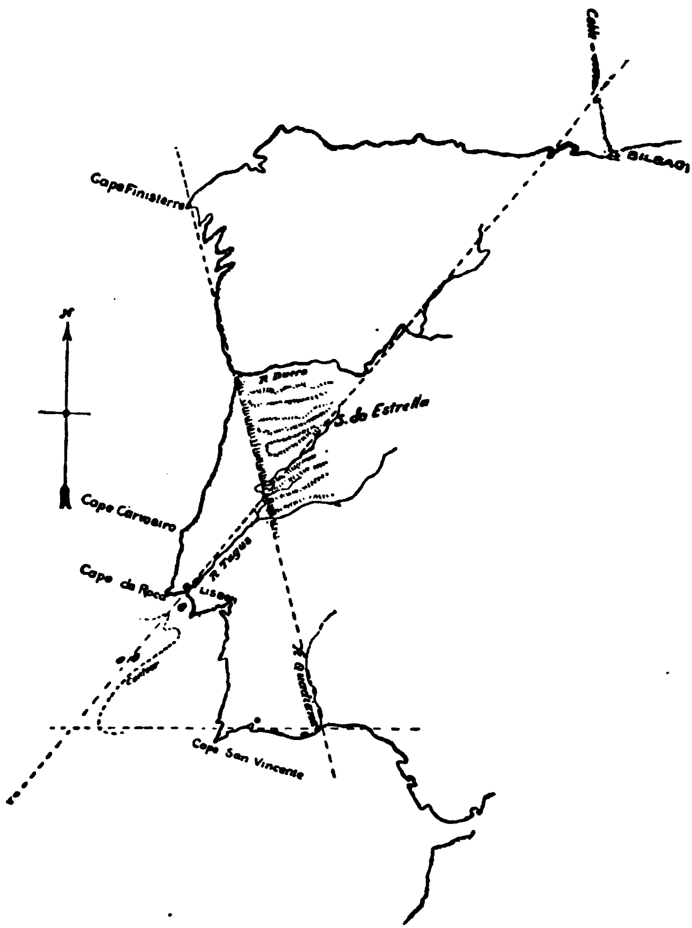

FIG. 56.—Sketch map of a portion of the Iberian Peninsula to illustrate the zones of special disturbance at the time of earthquakes. The spots indicated to the southwest of Lisbon are the localities where ships felt the shocks of the great Lisbon earthquake.

which borders the Tagus lineament on the west, was split and rent in a most remarkable manner and threw down great avalanches of rock into the valley. The ships upon the high sea which felt the shocks were all in the vicinity of the same lineament.

In Lisbon itself, notwithstanding the great intensity of the shocks, some houses remained standing unharmed, though surrounded by utter destruction. The new Lisbon quay, which had been built entirely of marble, suddenly sank down into the bay with an immense crowd of people, who had gathered in supposed safety upon it, and the reports state that no one of the bodies ever floated to the surface.

The great water wave.

Following hard upon the first shocks, the sea retired from the land, carrying boats and other craft with it, only to return in a great wave sixty feet in height, which completed the destruction in and about the city. This great sea wave, the mightiest which has ever been described in connection with an earthquake, is reported to have washed not only the coast of the Iberian Peninsula, but to have extended with destructive violence to the coasts of many distant countries. At Kinsale in Ireland it was strong enough to whirl vessels about in the harbor and to pour into the market place, and it was of great violence also at the island of Madeira. It has generally been assumed, and we believe without warrant, that it was one and the same water wave which produced all the recorded disturbances. It is much more probable that other and sympathetic earthquake disturbances acted in essentially the same manner, though started from different areas.

The great earthquake which shook Calabria and northeastern Sicily in the year 1783, stands out in rather

striking contrast with other disturbances of that early period, for the reason that it was carefully studied by a number of men of more than average ability and trustworthiness. Among them were Vivenzio, the court physician of the King of Naples, who has supplied us with a narrative of the events; Grimaldi, the minister of war, who at the king's command personally visited the region, and has supplied us with accurate measurements from the faults and other fissures; Pignaturo, the physician at Monteleone, who kept a record of the shocks, together with their estimated intensities, for both the years 1783 and 1784; the French geologist Dolomieu, who personally visited the district; and Sir William Hamilton, England's distinguished representative at the court of Naples. Not content with the studies of these gentlemen, the Royal Academy of Naples sent a delegation with a staff of artists, and prepared a bulky report of the greatest scientific value. No earthquake, ancient or modern, has been more carefully studied.

The great Calabrian earthquake of 1783.

Calabria is a country which has many times been racked by earthquakes, and for no other country save Japan have the records been so long or so well preserved. The areas shaken have not been extraordinary for extent, but as regards both the geological changes and the losses to life by which they have been accompanied, they rank among the greatest in history.

The shocks of 1783, which cost 30,000 lives, came without warning on February 5, 1783, and in the space of two minutes threw down the structures in numberless cities and villages scattered through Calabria and northeastern Sicily. The great central granite mass of Calabria, which was but slightly disturbed by the first shock, was more heavily shaken by those which followed.

It was noted by the early writers upon this earthquake that the shocks were most violent along the junction of the recent strata with the granite and other crystalline rocks. These latter rocks rise on steep slopes from the newer strata which compose the Calabrian plain, and it was found after the earthquake that the mountains had been relatively elevated so as to cause the looser material to slide downward from their margins, and in places leave a gaping chasm along the junction. Such a chasm, it has been suggested, might well account for the fact that so many of the rivers of Italy follow the sharp junction of the newer with the older and firmer rock masses.

irection of he shocks.

During the earthquake the surface of the country heaved in great undulations which were productive of nausea, and which gave the effect of the clouds having suddenly become motionless—an effect which is often observed from the deck of a tossing ship. Large trees swayed by the rocking earth were so bent that their tops touched the earth. In some localities the shocks were vorticose, for obelisks which adorned the façade of the convent of San Bruno at San Stefano were curiously twisted. In each case the pedestal remained undisturbed, though the stones composing the obelisk had been turned upon their bases through considerable angles, which increased with the height of the block above the base. At some places, also, the shocks were nearly vertical in direction, for objects such as paving stones were thrown up from the surface of the ground to a height of several yards and were often overturned in falling. At Terranuova a stone well was projected out of the ground, and in its new position resembled a small tower eight or nine feet in height.

The fissures which appeared in the ground at the time of the earthquake were numbered by thousands, and were

found in many parts of the disturbed region. On many of these fissures displacements had occurred which, in some cases, amounted to as much as ten feet.

Faults and fissures.

Along the great fault line which follows the straight southeastern coast of Sicily, movement was especially noticeable at Messina, where the shore was rent and tilted seaward so that the quay sank fourteen inches, and the sea bottom was not only depressed in places, but rendered very irregular. In Terranuova some houses were elevated above the general level of the ground, while other neighboring houses were depressed by varying amounts. A large and circular masonry tower was, by a vertical fissure, divided in half, and the one side elevated so high that the foundations were brought above ground. Yet so closely were the two parts pressed together that the only evidence of the fracture in the walls of the tower was the failure of the stone courses to match on the two sides. In the city of Monteleone nearly every house was demolished on certain streets, and nearly all left standing upon others.

Opening and closing of fissures.

The healing of the fracture in the Round Tower of Terranuova indicates that after the fissure had opened sufficiently to permit the displacement, it was again closed under pressure. There were many more striking illustrations of such alternation of motion in the earth blocks. Many fissures were observed to open and close alternately, and instances were not lacking where men and cattle were first engulfed in the fissures and later thrown out alive by succeeding shocks, accompanied by a large volume of water and sand. The closing of the fissures is said to have taken place violently, so that the walls were pressed hard against each other. Certain houses which had become engulfed in the fissures were

afterwards exhumed and found to have had their sides jammed together into a compact mass extended along the plane of the fissure. Such violent closing of the opened fissures was not, however, universal; for the academicians who visited the district state that fissures which they had observed on entering the district were found to be partly closed at the time of their return. Other fissures, which had opened with the first shock of the earthquake on February 5, were found to have been greatly widened, lengthened, and deepened, at the time of the shocks on March 28. Some of these fissures, which were generally straight, were found to be nearly a mile in length and two hundred feet in depth.

At Gerocarne, the surface of the ground was said by the academicians to be "lacerated," and the fissures here generally ran from centers so as to produce a roughly stellate appearance (see Fig. 27, p. 79), like cracks in a pane of glass. In general, however, it was observed that the fissures ran either along the junctions of the older and more rigid formations with the newer and loosely consolidated ones, or parallel to the ravines and gorges which had before existed in the region.

[Ci]rcular [ho]llows and [s]and cones. Some of the Calabrian plains were found after the earthquake to be dotted with circular hollows, which, upon the average, had the size of carriage wheels, and which, when filled with water to within a foot or two of the surface, appeared like wells (see Fig. 28, p. 80). More often, however, they were filled with dry sand, with which were admixed scales of mica, and presented either a concave or a convex upper surface. Upon digging down in them they were found to have the shape of inverted cones continued downward into the ground as a relatively small shaft or pipe in which the sand was moist,

and up which water had spouted at the time of the earthquake. In many places, also, were found an immense number of sand cones not essentially different in their origin from certain of the circular hollows which were found filled with sand.

Derangement of the surface water. In addition to the well-like pools of water which occupied the circular hollows above described, there were other water basins more deserving the name of ponds or lakes. One of these, in the vicinity of Seminara, to which the name of Lago di Tolfilo was given, was about a third of a mile in length, and was so copiously fed by the springs ranged on a fissure in its bottom, that all attempts to drain it proved futile. Near Sitizzano a valley was completely choked up by the landslips from opposite sides, and behind this new dam a lake was formed which was about two miles in length and one mile in breadth. Vivenzio states that fifty lakes arose at the time of the earthquake, and the government surveyors, who included smaller ponds, counted no less than two hundred and fifteen. The first effect of the more violent shocks was generally to dry up the rivers, immediately succeeding which they were filled so as to overflow their banks.

Landslips and mud torrents. The valleys of Calabria, and especially those near the coast, are for the most part deep ravines cut in loosely consolidated rocks, and in the rainy season they become so saturated with water that even slight shocks cause the banks to suddenly slide downward into the bed of the stream. As earthquakes are frequent throughout the province, it is seldom that some scars due to this process are not to be observed on all the deeper gorges. During the great earthquake of 1783 the great volume of water which welled up from below along the lines of these ravines so modified the usual process that the soil

has been described as "dissolved" into great torrents of mud which inundated all the low grounds after the manner of mud lavas in connection with volcanoes. One such mud stream, formed at the time of the great earthquake, presented a front of two hundred and twenty-five feet, with a depth of fifteen feet.

ll of sea ffs and undation Scilla.

Reference has already been made to the geological changes which occurred at Messina along the course of the great fault which passes between Scilla and Charybdis at the Straits of Messina and, continued southward, forms the steep, rocky, eastern coastline of Sicily. From the rock of Scilla large sections of cliff were broken off, and at one place a section a mile in length was thrown down. The sea in the vicinity was greatly disturbed, and fishes of rare species which usually lie buried in the sand came to the surface in large numbers. Soon after the fall of the cliffs near Scilla the sea rose to a height of twenty feet and rolled back over the low-lying tract below the cliffs. The Prince of Scilla, who had induced his subjects to follow his example of seeking safety upon the water, was among the 1,500 destroyed by the wave.

he Mino-wari earth-uake in apan in 91.

The Empire of Japan is, as regards its land area, perhaps as unstable as any upon the globe, and the records of its earthquakes are probably as complete as any that are in existence. The total number of recorded destructive earthquakes in a period of nearly fifteen hundred years is two hundred and twenty-three. Since the beginning of the seventeenth century the records are fairly perfect, and it is found that a destructive earthquake has occurred somewhere in the empire once every two and a half years. For the lighter shocks systematic earthquake observation is necessary, and an earthquake

service was first organized in 1885. Since that time the earthquakes of all intensities recorded from Japan give a yearly average of fourteen hundred and forty-seven shocks, or a daily average of four. Until the great earthquake of 1891 in the twin provinces of Mino and Owari, the greatest shocks within the memory of living men were those of 1854–55.

The earthquake of October 28, 1891, shook an area of 243,000 square miles, or more than three-fifths of the entire area of Japan. The area shaken with catastrophic violence was much smaller, and was largely confined to the two provinces above mentioned, which together occupy a broad plain occupied by rice fields extending northwestward from near the "elbow" of Japan, and surrounded on all sides but the south by high mountains. This kettle-shaped basin among the hills had, at least for a long period, not been troubled by earthquakes, which may help to explain the excessive violence of the movements in 1891.

Without the least premonitory symptom the stroke fell, and in the first moment was wrought the destruction of about 7,000 people and 20,000 buildings, while 17,000 people were more or less seriously injured. As has been true of so many other earthquakes, fires almost immediately broke out among the ruins and burned to death many who might otherwise have escaped. Throughout a large area situated near to the center of the affected district, the ground was riven by myriads of fissures. Small mud volcanoes and sand craters were numerous, and an open fissure a mile in length appeared along the banks of the Shonai River. Here, also, a bamboo grove with pines and thatched houses was shifted *en bloc* sixty feet back from the river embankment, the trees remaining upright, and

the thatched roofs falling to the ground without fracture. Over the great Mino-Owari plain most of the peasants' houses fell in this manner, so that from the distance they presented the appearance of gigantic saddles scattered over the plain. This plain is one of Japan's great gardens, and supported almost 1,000 people to the square mile. Villages were there almost continuous, and a narrow lane of unusual destruction could be traced through them for twenty miles.

e after ocks.

The numerous after shocks of the earthquake were carefully recorded at the cities of Gifu and Nagoya, those registered at the first-mentioned city appearing in the following table, which well illustrates how after shocks fade gradually away in number, as they do in intensity, after the initial heavy shocks. The suffering and terror of the first day sufficiently account for the apparent exception there to the law which otherwise generally obtains.

The After shocks of the Mino-Owari Earthquake, Registered at Gifu.

Oct. 28...102	Nov. 5...53	Nov. 13...35	Nov. 21...21
" 29...318	" 6...67	" 14...29	" 22...12
" 30...173	" 7...45	" 15...29	" 23...23
" 31...126	" 8...42	" 16...28	" 24...18
Nov. 1... 99	" 9...44	" 17...21	" 25... 9
" 2... 92	" 10...40	" 18...18	" 26...15
" 3... 81	" 11...38	" 19...17	" 27...11
" 4... 78	" 12...40	" 20...33	

During the first five months succeeding the initial shock, no less than 2,588 after shocks were recorded at Gifu.

Along the longer axis of the area most disturbed within the provinces of Mino and Owari, there appeared a great

earthquake fault extending in the general direction north-northwest and south-southeast, along which the land lying to the eastward was in general dropped down in reference to that upon the westward, and was also generally shifted along the fault to the north-westward (see Frontispiece Plate). The average amount of this northerly shifting (or southerly shifting of the opposite series of land blocks) varied from three to six feet. Exceptionally, this amount was much greater, as was indicated, for example, in the little hamlet of Jōbara, where, however, careful examination of the ground was necessary in order to determine where the crack had been formed. Two persimmon trees, which before had stood upon an east and west line, were afterwards aligned along a meridian, to the complete mystification of the inhabitants, who did not discover the crack, and perhaps would have been no wiser if they had (see Fig. 57). Where the fault cut the paddy fields, the low ridges used to separate neighboring fields were cut obliquely and offset, though without important vertical displacement (see Fig. 20, p. 66).

The Neo valley fault.

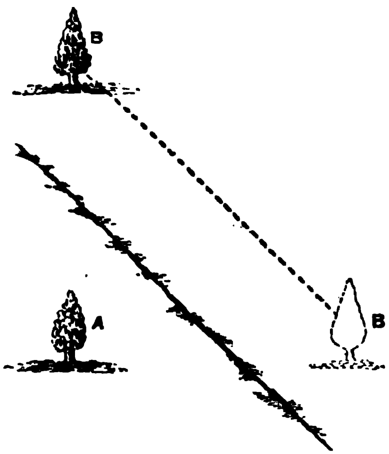

FIG. 57.—Lateral displacement upon the Neo valley earthquake fault as measured by the displacement of trees at Jōbara (after Kotô).

The vertical displacement upon the Neo fault, where less

than two feet, did not produce a vertical wall, but the ground rose from the lower to the higher level upon a curved surface which was transversely cracked and gave the effect of a gigantic mole track (see Fig. 58). Although the ground was generally lowered upon the east side of the fault, this was not always the case, nor was the throw of uniform amount. The best instance of large vertical displacement was furnished at Midori (see Frontispiece Plate, where it was no less than eighteen feet, and, further, *in the opposite direction* to that which was common along the fault. The lateral displacement was, however, here in the usual direction and measured about twelve feet.

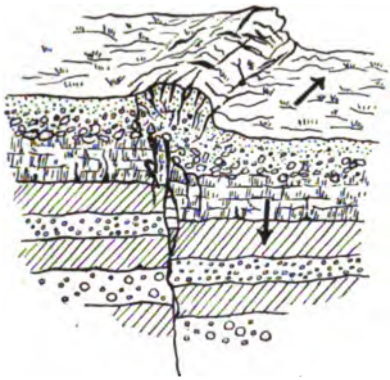

FIG. 58.—Sectional diagram to show how "mole track" or "plowshare" effect is produced over an earthquake fault (after Kotô).

The Neo valley fault was not the only, but rather the largest, of the displacements brought about at the time of this earthquake. At Omori innumerable fissures traversed the ground in a network of many directions, and some of the included earth blocks were raised, and others lowered, much as was the case at Big Pine, in the Owens valley, during the earthquake of 1872 (see p. 180).

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t of the
hage.

At Ishiwara an artificial reservoir which was fed by a stream and used to irrigate the paddy fields was cut by the fault in an east-west direction. The northern half was depressed as well as shifted, and the

southern half was drained. The water continued to enter the reservoir through the stream, but apparently soaked down into the ground along the fault line, as the level of the reservoir was not raised. The villages of Nishi-Fukasé and Higashi-Fukasé were by a depression of the ground transformed into a deep swamp two square kilometers in area.

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CHAPTER IX

SOME GREAT EARTHQUAKES DESCRIBED (*Concluded*)

landic thquakes 1896.

One of the most instructive earthquakes of which we have scientific accounts, is that which affected a triangular plateau area of southwestern Iceland in the early fall of 1896. Owing to the fact that the extensive study of it was printed in the Icelandic language, our knowledge of the facts dates from the publication in 1901 of a German summary. The area of the disturbance is bordered by a rampart of lofty mountains, included among which are Mount Hecla and other well-known volcanoes. These volcanoes were at rest before, during, and after the earthquakes, the destructive shocks of which occurred upon the 26th and 27th of August, and the 5th, 6th, and 10th of the following month.

ies own up n the face of earth.

During the shocks the earth's surface was thrown into waves so that neither men nor cattle could stand. It was noticeable that the shocks appeared to come from the boundaries of the plateau. In one village, which was situated upon a height composed of heavy lava rock resting upon a volcanic ash which was largely cemented into rock, a heavy stove six feet in height was thrown a distance of twenty-five feet. Persons who were lying upon the ground near a cliff were by the shock thrown bodily over its edge. An isolated hill, which rose

seven hundred and forty feet out of the plain, is described as shaken "like a poodle coming out of the water," and a thick mantle of loose soil which had covered it was afterwards found distributed in heaps about its base.

Earthquake faults and fissures.

The surface of the plain was outlined by open fissures or fresh rock walls, due to the land having been elevated upon one side of the fissure. Other faults and fissures crossed the area. One of these was open for about seven miles, and another was nine miles in length, and was accompanied by many other parallel faults. The mountains immediately surrounding the plain were riven by clefts, and landslips were common upon the steep slopes which bounded the plateau. In the high surrounding region, however, shocks were slight or even imperceptible.

Derangement of the underground water.

Along many of the fissures which were opened in the ground there appeared large funnel-shaped openings, and where these fissures crossed swamps or ponds their waters had been sucked down through the funnels. As in most volcanic regions, there are in this portion of Iceland many warm springs, as well as vapor jets, which are known as *fumaroles*. When the great shock came during the night of September 5th (the third destructive shock of the series) a new spring opened, and to the accompaniment of loud roaring and whistling, threw water, steam, and fragments of volcanic rock to a height estimated at six hundred feet. Its force was, however, soon spent, and a few hours later it played but ten or twelve feet into the air. Ten days later it had ceased to flow. The region of disturbances is one of the three important geyser districts of the globe, and many well-known geysers suffered changes from the shocks. The famous *Strokkur*, which had come into being during the earthquake of 1789,

suddenly stopped erupting, and appears now to be quite dead. Cold springs and wells were no less strikingly deranged at the time of the earthquake, some drying up and new and permanent springs being formed. The surface water in brooks and ponds was made roily.

The most remarkable feature of this earthquake was the unusually striking limitation of the damage from each of the five destructive shocks to a particular area bounded by straight fissures and different for each of the shocks. The areas were generally contiguous to each other (see Fig. 59), and it thus

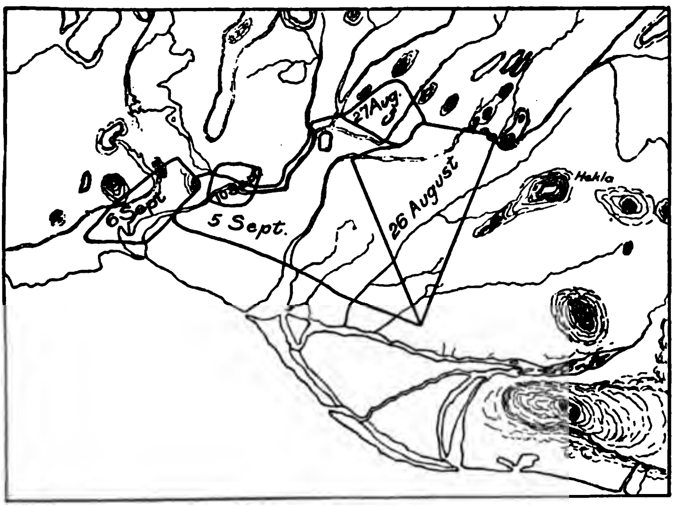

FIG. 59.—Sketch map to show the sections of country moved in succession by the Icelandic earthquake of 1896 (after Thoroddsen).

appeared that the earth's crust, in respect to the disturbances, was moved in definite sections or blocks, which were outlined by the surface fissures.

Great Assam earthquake of 1897.

Perhaps the greatest earthquake which has been recorded was that of Assam, India, which occurred upon June 12, 1897. No earthquake except that of Calabria in 1783 has been so fully or so ably studied, and the results, which are well illustrated, completely fill a bulky volume of the "Memoirs of the Geological Survey of India." Unlike the last-described earthquake, almost the total damage was here the result of the initial shock. Everything was destroyed within the first fifteen seconds of the disturbance, and the heavy shocks had all passed before two and a half minutes had elapsed. In this brief interval an area of one and three quarter millions of square miles had been shaken, and one hundred and fifty thousand square miles had been laid in ruins.

The phenomena at Shillong.

A member of the staff of the Geological Survey of India, who was in the town of Shillong at the time of the earthquake, has stated that a rumbling sound, like near thunder, preceded the shocks by a second or two of time, and increased in intensity, so that the falling of heavy masonry buildings a few rods away was not distinguishable. Unable to keep his feet he sat down upon the ground, and not only felt but distinctly saw the ground thrown into violent waves, "as though composed of soft jelly." These waves appeared to advance along the ground, and induced in him a feeling of nausea akin to seasickness. When the shocks had passed, all masonry structures had been leveled with the ground, and over each hung a cloud of pink plaster particles and dust. Above the town in the park a horseman noticed that a peculiar rustling of the leaves upon the trees preceded the first shocks by a brief interval of time, as though resulting from an earlier tremor.

By many the shocks were described as in places gyra-

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tory or twisting in their nature, and many monuments which were built up of sections revealed an increasing amount of rotation for those higher blocks in the structure which had not been completely detached.

faults
fissures.

Over large areas the surface of the ground was rent by numerous fissures, large or small, and some of these had great extent. It was noticed that these fissures followed in their direction the lines of the ranges of hills. Sometimes they gave the appearance of having opened and later closed under great pressure, as the ground was raised in a furrow. If sandy, the ground appeared as though a steam plow had passed over it, tearing up the surface and throwing heavy clods in every direction. Posts were sunk deeper into the ground, and were surrounded by a cup-shaped depression, so formed as to give the impression that they had been twisted (see Charleston Earthquake, Fig. 29, and p. 86). In many instances houses were similarly projected into the sandy ground, so that only their roofs remained visible.

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ntains.

In addition to the numerous cracks, crater-like pits were formed in the ground. These were usually about six feet across, though sometimes more, and through them jets of sand and water were thrown to a height of seven or eight feet and probably much higher (see Plate X). Mixed with the sand were fragments of peat, coal, resin, half-petrified pieces of timber, and a black earth unknown at the time within the district. The same materials also welled up through some of the fissures. The large amount of sand thus brought to the surface was spread around the orifices in flat domes, and where these were most numerous the entire face of the country was flooded, and after an interval blanketed with a layer of

quicksand in which cattle floundered and were held fast. The local streams were suddenly swollen and raised from two to ten feet, though they settled back to their former levels shortly afterwards. The Brahmaputra advanced as a wall of water ten feet in height.

The effect upon rivers.

In the Garo and Khasi hills the numerous landslips within the weathered sandstone rocks developed widespread fans of sand at their bases. The rivers of this section are ordinarily a series of deep pools separated by rocky rapids, which in flood time change to raging torrents. Following the rains after the earthquake of 1897, the pools were found to be filled up with sand, the rapids obliterated, and the streams flowed over the sandy floor of a broad and shallow channel. In this hill country were found the most interesting of the geological changes. Though only a single zigzagging journey was made through the country, three large earthquake faults, hundreds of great fissures, and no less than thirty lakes were found to have resulted from the earthquake. One of these lakes was more than a mile and a half across.

The great Chedrang fault.

The largest of the earthquake faults, known as the Chedrang fault, adhered to the course of a meandering but otherwise straight river, and was thus followed for a distance of twelve miles. The vertical displacement or throw revealed by the walls of this fissure was in one place no less than thirty-three feet, but it changed most abruptly, as is indicated by the sketch map of Fig. 60. Where the upthrown side cut the course of the river on the downstream side, the waters had been impounded into a lake, but otherwise a waterfall only resulted. Sometimes the fault was double, and examination of a ledge of rock two hundred feet distant from it showed that adjustments, amounting to several inches, had oc-

curred upon many of the vertical joints by which it was intersected. The Samin fault was also traced between two and three miles and found to have a maximum vertical

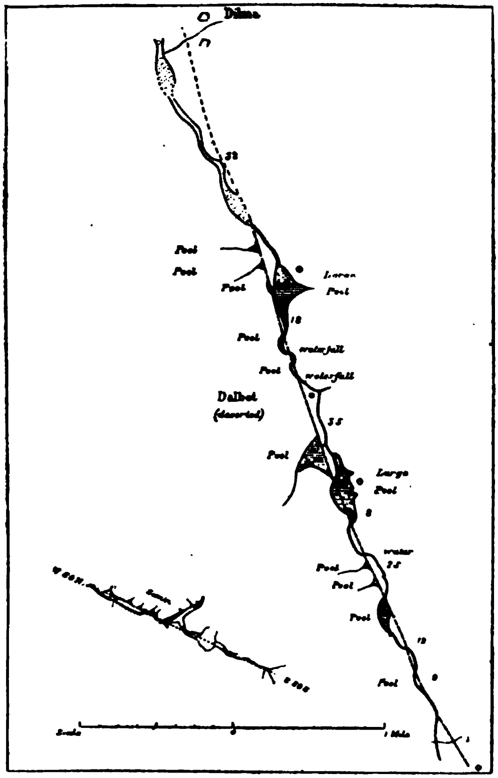

FIG. 60.—Map of the Chedrang and Samin faults produced at the time of the Assam earthquake of 1897 (after R. D. Oldham).

displacement of about ten feet. Throughout, the movements appear to have been upon essentially vertical planes.

Overturning of heavy bodies near fault.

At one place along the course of the Chedrang fault a tilting of the ground in the direction of the course of the fault was noticed, and small lakes were produced as a result. A roughly cubical block of granite forty feet long, thirty feet wide, and thirty feet high, which had lain across the course of the fault, had

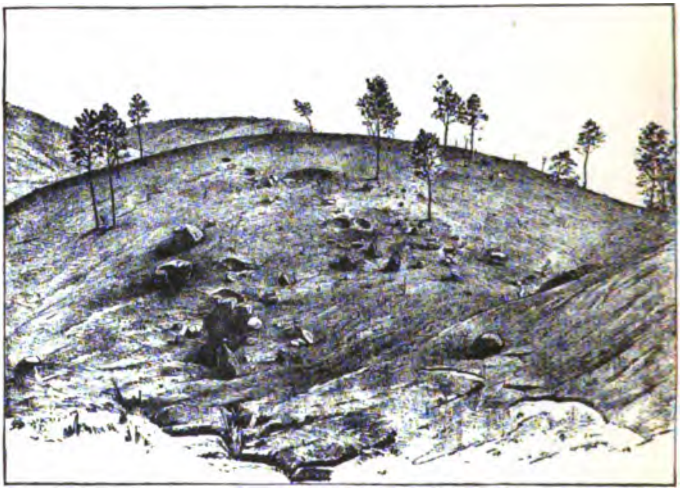

FIG. 61.—Bowlders near Kanchi projected upward and overturned by the shocks of the Assam earthquake of 1897 (after R. D. Oldham).

by the movement along it been completely overturned (see p. 84). Elsewhere in the vicinity large bowlders were seen to have been lifted out of their hollows, projected for a considerable distance, and left in some instances with the dirty side uppermost (see Fig. 61).

In the report upon the earthquake the name "fracture" is given to the numerous visible fissure planes on which no observable vertical displacement, or at most a very small

one, could be made out. Of these there were hundreds observed, of which the largest was described as the Bordwar fracture. This was followed for about seven miles in a straight line as a crack in the hard gneiss rock, and showed at places a few inches of displacement. Its course could, however, be easily followed by overturned trees, broken bamboos, landslips, or as a small ditch in the surface of the ground.

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Important changes of level of great blocks of country were clearly shown by the alterations in the aspect of the landscape. Ranges of hills, which before had not been visible from certain points, now came for the first time into view, while others had disappeared. In at least one instance some measurement of these changes was carried out. So soon as it was noted that they had taken place, lines of sight to definite points in the landscape were determined through the nailing of boards to stout posts. Later observations along the same lines gave some measure of the subsequent changes of the same character. Shortly before the earthquake, a primary triangulation of the district had been carried out. A resurvey subsequent to the disturbance revealed changes of elevation of stations by as much as twelve feet. and of location by about the same figure.

he after hocks.

Though the most destructive shock arrived during the first few seconds of the disturbance, those which immediately followed were heavy enough to have caused great damage had not all structures been already leveled. Shocks of lesser intensity were felt for more than a week, but these gradually faded away. At a point located near the Chedrang fault, it was noticed that the surface of a glass of water did not come to rest for more than a week after the disturbance. Observations

proved, however, that after shocks were less numerous in the vicinity of the faults than elsewhere within the affected region. When the shocks had become no longer perceptible as waves, they continued to be detected as low, rumbling sounds. Of observations which extended over twenty-three hours, forty-eight disturbances were noted, only seven of which were accompanied by sensible shocks. This earthquake is, further, of especial interest as the first one to be registered at a number of distant seismological stations, several of which were located in Europe.

Earthquake of northern Honshu (Japan) in 1896. On August 31, 1896, a heavy earthquake visited the province of northern Honshu, Japan. Unlike most heavy earthquakes, this was preceded by weak shocks which were felt six or eight hours before the main blow fell. It is this which in part accounts for the fact that the casualties did not exceed 1,000. Thirty-three hours before the big shock there was also a strong magnetic disturbance. Almost exactly coincident with the arrival of the heavy shocks, two great clefts—the Kawafune and Senya clefts—opened on opposite sides of a mountain range which forms the backbone of Japan in this province (see Fig. 62). The land blocks lying outside these clefts were dropped by some yards, and between the clefts the shocks are said to have been the most severe. Beyond where the fractures could be followed, an extension of the area of high intensity was noted, and a lane of ruined villages continued the fault direction. Along the Kawafune cleft to the east of the Mahiru range of mountains, the land was separated so that one side was raised six feet with reference to the other. Where this fault crossed a fish pond all the fishes were sucked down with the water. Generally the fault wall was steep, but in some places it exhibited the "mole-track" effect so often observed in con-

nection with Japanese earthquakes. Near the village of Kawafune the fault crossed and soon recrossed a crooked road and left the intervening block one yard higher, and about the same distance farther east, than the country

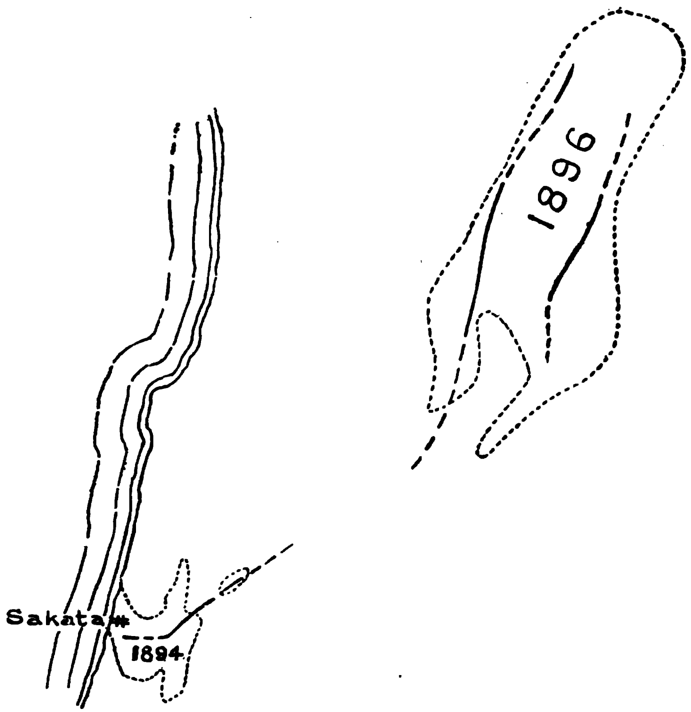

FIG. 62.—Map of the faults formed during the great Japanese earthquakes of 1894 and 1896 (after Yamasaki).

opposite. A small house which before had stood exactly over the line of the cleft was stood upon its head, but without receiving special injury. The entire length of this cleft was 15 kilometers, or about 10 miles.

The Senya fault. Along the Senya fault, which ran nearly parallel to the Kawafune fault and was upon the other side of the range, the throw took place in the opposite direction and by an amount varying from one to two yards. At Uzumaki, on the Tama River, there had before existed a roaring rapid. This rapid was obliterated by the displacement at the time of the earthquake through the dropping down of the upstream portion of the river. The fault maintains its course at the foot of the range and near the border of the surrounding alluvial plain, and it was here that the destruction was the greatest. At Sheroiwa a parallel crack was formed to the two main ones. At one place the Senya fault disappeared suddenly from view and was not found for a distance of 12 kilometers (about 7½ miles), at the end of which interval it again suddenly appeared as a displacement a meter high, and in this form it continued for another 10 kilometers (about 6.2 miles). Beyond this last point the crack could not be observed, but its continuation below the surface of the ground was followed without difficulty in the lanes of destruction through native villages. The entire length of the Senya cleft was 60 kilometers and its greatest vertical displacement about 10 feet. Having in mind the gap of no less than 12 kilometers between the extreme portions of the cleft, it is easy to understand that this great fault is but the continuation of the Yadare-Sawa cleft which was formed during the earthquake of October 23, 1894, some distance farther to the southwest, near Sakata (see Fig. 62).

The usual derangements in the flow of ground water occurred in the province at the time of this earthquake. In the flood plains of the rivers small fissures appeared on which craters were ranged, and important changes occurred in the volume of springs. Certain thermal springs

Statue of Queen Victoria in the Park at Kingston, Jamaica, which was Turned on Its Pedestal during the Earthquake of January 15, 1907. (After a photograph by Brown Bros.)

dried up completely, others diminished in volume, and some new ones came into existence with the earthquake.

The Kingston earthquake of 1907.

The island of Jamaica in the American Mediterranean has its record of earthquake disasters, with the port of Kingston a focus of the recurrent shocks. The city of Kingston is shielded from the sea by a seven-mile sand spit, at the extremity of which is Port Royal, His Majesty's naval station (see Fig. 63, *c*). In the year 1692 Port Royal, the then city, was destroyed, and in rebuilding the city it was moved across the harbor to its present site at Kingston. The old town site was at this time in large part submerged beneath the sea, due to a settlement of the ground, and it is worthy of note that a continuation of this settlement has lately occurred.

The main shock of January 14, 1907, was preceded at about 3.30 o'clock in the afternoon by slight tremors, a very brief interval only in advance of the main shock. A resident of the city who was accustomed to earthquakes rushed out of doors when the first sound was heard, and on reaching the street was almost immediately thrown down. After regaining his feet and dragging an injured man a distance of about 100 feet, he experienced a second maximum of rocking of the ground. The testimony seems to be in agreement that the heaviest shock was not more than ten seconds behind the first subterranean rumbling (probably considerably less), and that a second and lighter shock followed the first after about twenty seconds, and that, further, all damage had been done before thirty-five seconds had elapsed. Some eighty after shocks of this earthquake were recorded between June 14th and February 5th, 1907, and still others were felt, especially on February 23d and March 22d.

Within the city of Kingston the east and west walls of

buildings were the ones most generally overthrown, showing that the shocks were here strongest from these directions. This accords well with the direction of strong motion felt by individuals in the city. As regards the distribution upon the island of Jamaica, the shocks seem to have been strikingly localized at Kingston and Port Royal on the southeast coast, and at Bluff and Annota bays on the northeast coast, where the destruction was but little less than at Kingston. Upon the line joining Kingston and Bluff Bay is Newcastle, and it was upon the mountain road joining these cities that the evidence of heavy shocks was greatest. The strong seismotectonic line thus indicated as connecting Kingston, through Newcastle, with Bluff Bay, when extended northward passes through Santiago de Cuba, which of the distant points seems to have been the one specially singled out to feel the shocks.

Nature and distribution of the shocks.

Another seismotectonic line, or rather narrow zone, was indicated to pass in a direction a little north of westward through Kingston and Port Royal and to intersect Mandeville and Savanna la Mar. East of Port Royal, the cable to the city of Colon, upon the Isthmus of Panama, was fractured four miles out from Bull Bay, where it intersects another lineament of the island (see Fig. 63). This cable sustained a second fracture at a point sixteen miles farther out, or twenty miles from its terminal at Bull Bay.

A third seismotectonic line of the island of Jamaica passes from Bluff and Annota bays in a direction west-southwestern through Mandeville. The two seismotectonic lines first mentioned intersect at Kingston, and an examination of the maps will show that the direction of heaviest shocks was parallel to the course of seismotectonic lines in the immediate vicinity. The localization of the heavy

PLATE XIII.

A. A series of parallel step faults at the base of the Palisadoes which represent an aggregate displacement of twenty-four feet.

B. View looking east along one of the great fissures at the base of the Palisadoes, which has mud craterlets aligned along it.

VIEWS AT KINGSTON, JAMAICA, AFTER THE EARTHQUAKE OF JANUARY 15, 1907. (After photographs by Charles W. Brown.)

damage at Kingston and at Bluff Bay, and the rotation of monuments may be thus explained.

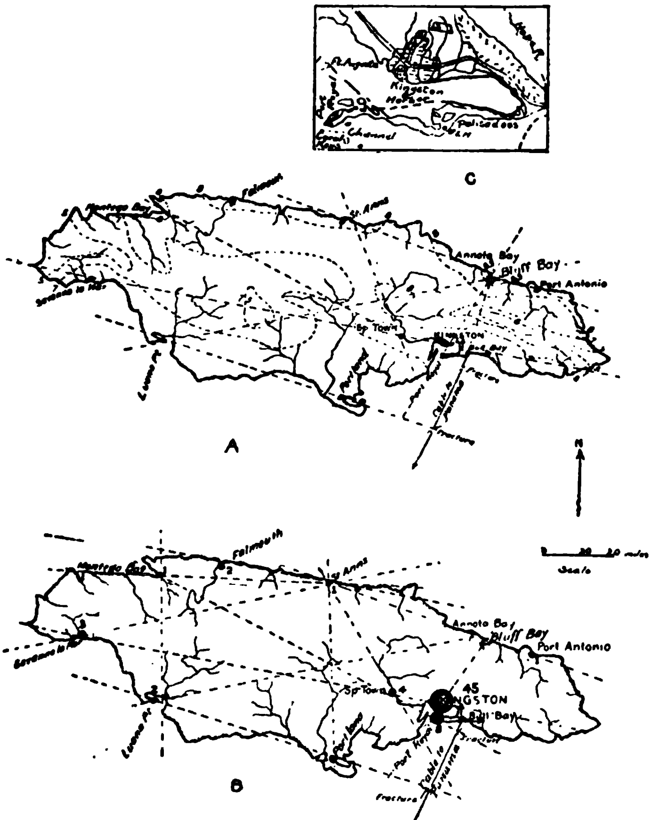

FIG. 63.—*a*, Sketch map of Jamaica to indicate the distribution of intensity of surface shocks during the earthquake of 1907 (data after Brown). *b*, Sketch map of Jamaica setting forth the habitual epicenters of the island (data after De Montessus). *c*, The harbor of Kingston, showing the zone of submergence due to the recent disturbances (after Brown).

The best-known instance of vorticose motion resulting from the shocks is furnished by the fine statue of Queen Victoria in the city of Kingston, which was turned upon its pedestal an eighth of a revolution in a direction opposite to that of the hands upon a clock face (see Plate XII). How well the seismotectonic lines indicated by the recent disturbance were foreshadowed by the lines joining habitual epicenters, as determined by De Montessus, will be apparent by examination of Fig. 63, *b*.

Step faults and craterlets. The visible faults due to the Kingston disturbance were mainly to be found within a zone which surrounds upon all sides the inner harbor of the port (see Fig. 63, *c*). Upon the inner margin of the sand spit which incloses so large a portion of the harbor, a series of parallel faults was formed, with their throw progressively downward in a direction toward the shore. These faults have produced, therefore, a series of steep terraces—step faults—upon which a total vertical displacement of no less than twenty-four feet was measured (see Plate XIII, *A*). Where one of these faults intersects a railroad in the Victoria battery, a sharp local kink has resulted, such as has been often described in connection with other great earthquakes (see Plate XIV, *A*).

These faults are reported to have repeatedly opened and closed, accompanied by intermittent ejection of water, sand, and mud with such force that fountains of the material three or four feet in height resulted. These sand and water fountains left the fissures half filled with sand, which was also distributed outward from their lips, while the elevated bottom of the fissure exhibited an almost continuous series of craterlets (see Plate XIII, *B*).

What formerly had been a small spring near the east end of the harbor was at the time of the earthquake increased

A. Subsidence of the ground with consequent tilting of buildings in the Victoria Battery, Port Royal. The kink in the railway track is over a fault.

B. Near view of the submerged area at Port Royal, looking south. Most of the area in the view which is covered by water was land prior to the earthquake.

VIEWS AT KINGSTON, JAMAICA, AFTER THE EARTHQUAKE OF JANUARY 15, 1907. (After photographs by Charles W. Brown.)

in volume until a stream eight feet in width and six inches in depth flowed away from it.

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The late importance of Port Royal as His Britannic Majesty's chief naval station in the American Mediterranean, is in part responsible for the excellent series of soundings of the sea bottom in and about the island. The few soundings which have been made within the inner harbor since the disaster show that very important submergencies have occurred, and apparently these are greatest within the marginal zone near the series of step faults already described. The increase in depth of the harbor since the earthquake is in one instance not less than twenty-seven feet. The maximum depression took place near the western end of the peninsula, where is located Port Royal (see Plate XIV, *B*), and where a hundred yards or more of the ground was submerged by an amount varying from eight to twenty-five feet. The roofs of casemates and the canopies of palms now show above the water's surface to outline the area of the latest submergence, which has occurred in succession to that of a still larger section of land, together with the former city, in 1692.

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CHAPTER X

GREAT EARTHQUAKES WITHIN THE TERRITORY OF THE UNITED STATES

Earthquake of the lower Mississippi in 1811.

THE earthquake shocks which in the winter of 1811–12 produced the "sunk country" and the "sand slew district" along the lower Mississippi River, were felt throughout the entire eastern portion of the United States and as far west as exploration had gone. In common with other earthquakes which have affected alluvial plains, this one was characterized by very extensive derangement of the ground water, and it was further especially worthy of note by reason of the sulphurous gases emitted and the long continuance of the after shocks. We are fortunate in the preservation of several excellent and apparently conservative accounts of it, and the region has been recently examined with special reference to the geological changes which were wrought at the time of the earthquake.

At New Madrid, near the center of the district, subterranean thunder appears to have been frequently heard for many years preceding the earthquake, but for the last twelve months it had not been heard. About two o'clock in the night of December 16, 1811, there came a severe earth shock accompanied by a noise which resembled loud and near thunder, although more hoarse and vibrating,

and this was followed in a few minutes by saturation of the atmosphere with sulphurous vapor. This vapor has been described in connection with subsequent shocks as of a purplish hue and resembling smoke and "Indian summer." North of New Madrid the current of the Mississippi River was reversed in direction for a period measured in minutes. After light shocks had been almost continuous until sunrise, one more violent than the first occurred. Between December 16, 1811, and March 16, 1812, no less than 1,874 shocks were recorded, of which number eight were of the first order of intensity.

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The shock of January 23d, though as violent as any which had preceded it, was surpassed by the so-called "hard shock" which came at about four o'clock in the afternoon of February 7th, and was accompanied by a charge of sulphurous vapor in the atmosphere and an unusual darkness which added greatly to the terror of the people. The Mississippi seemed to recede from its banks, and "its waters gathered up like mountains, leaving boats high up on the sands. The waters then moved inward with a front wall fifteen to twenty feet perpendicular, and tore the boats from their moorings and carried them up a creek closely packed for a quarter of a mile. The river fell as rapidly as it had risen and receded within its banks with such violence that it took with it the grove of cottonwoods which hedged its borders. They were broken off with such regularity that in some instances persons who had not witnessed the fact could with difficulty be persuaded that it was not a work of art."

...faults ...fissures.

During all the hard shocks the earth's surface was reported to have been raised into great undulations, the crests of which soon parted. From fissures thus formed, some of them 600 to 700 feet long and

20 to 30 feet wide, water and sand spouted upward sometimes to a height of 40 feet, and with the sand were abundant particles of coal. The surface of hundreds of acres was from time to time covered over to various depths by sand which issued through the numerous fissures. In the neighborhood of the fissures there was heard a roaring and whistling, and from certain of them a black liquid, doubtless thin mud, rose to the bellies of horses, which were standing motionless, struck with terror.

Seven years after the earthquake the geographer Flint visited the region and found hundreds of the fissures still open. Sir Charles Lyell, who explored a portion of the district in 1846, states that the fissures which he saw were often parallel and directed from 10° to 45° to the west of north. Another observer who has examined a portion of the district has described a majority of the fissures which he saw as parallel and directed along the meridian. In the Big Bay district there have recently been found two parallel east-and-west faults, evidently formed during the earthquake of 1811, as well as others tending northeast and southwest. It is a fact of some interest that these directions correspond to those of the faults and joints within the Ozark Mountains which rise to the west of the area. Upon the faults displacements of as much as four feet may be measured to-day.

Emission of sulphurous vapors. The walls of the earthquake fissures were in many cases found coated with what appeared to be sulphur, and the water of the Mississippi, for a distance of 150 miles, is said to have been so tainted with sulphur as to be unfit to drink. The emission of sulphurous vapors has been often mentioned in connection with earthquakes, and doubtless usually results from the liberation of sulphureted hydrogen formed as a product of putrefac-

A. A View on Reelfoot Lake which was Formed during the Earthquake in the Lower Mississippi Valley in 1811. The dead stump is from a tree snapped off at the time of the earthquake; the other trees with enlarged butts are of later growth. (After a photograph by Shepard.)

B. Cultivated Fields near Saikoseki, Formosa, Blanketed by Sand to an Average Depth of Two Feet during the Earthquake of March 17, 1906. (After Omori.)

tion within the loose upper soil, from which it is set free along the numerous fissures. The importance which such vapors acquire in connection with the New Madrid earthquake appears to be much greater, and the abundance and agreement of the testimony concerning the atmosphere immediately after the hard shocks is convincing.

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In the Gulf Plain sulphur is found associated with petroleum in the mounds of the neighboring oil field—mounds which it has been suggested may have come into existence at the time of this earthquake. The "coal" which was ejected with the sand along the fissures has upon examination been found to be lignite, which, like the sand, has been derived from a basin-like layer far below the surface of the ground. Above this layer of sand and lignite there is found an impervious layer of clay which imprisons the water under pressure and yields artesian wells where it is punctured. Such wells with sufficient pressure to flow at the surface are common in the surrounding country, but the upward leakage along the faults of the earthquake district lowers the pressure to such an extent that no flowing wells are there found. To-day a large volume of this water comes to the surface in a series of springs aligned along the fissures. In both springs and wells the fine white sand from the deep layer is brought in quantity to the surface, and the metal strainers which are used to cover the bottoms of the well pipes are, through its cutting action, destroyed in a surprisingly short time.

d cones craters.

After the earthquake shocks large areas of the disturbed country were found covered with holes which, upon a smaller scale, resembled the craters of volcanoes and were surrounded by a ring of sand and carbonized wood sometimes as much as 7 feet in height.

A few months later these craters were sounded and found to exceed 20 feet in depth. Composed largely of white sand, no vegetation has taken root upon the slopes of these craters, which even to-day are marked off as barren mounds 3 or 4 feet in height, with a diameter of from 20 to 100 feet, and sometimes slightly hollowed at the center.

Changes in level of sections of the plain.

Notable changes in level of large tracts of country were the result of the earthquake. Within the region lying between the mouth of the Ohio at Cairo and the St. Francis River, a distance of some 300 miles, new lakes and islands came into existence. Near Little Prairie a lake appeared many miles long and 3 to 4 feet deep, which upon its disappearance later left behind a stratum of sand. On the other hand, a former lake known as Lake Eulalie, 300 yards in length and 100 yards in width, was suddenly drained; and in 1846 the parallel fissures upon its bottom, through which its water had escaped, were still to be seen. Other similarly drained lakes revealed bottoms which, in alternating strips, had been uplifted and depressed. Upon the eastern bank of the Mississippi a lake 100 miles long, 6 miles wide, and from 10 to 50 feet in depth was formed as a result of the earthquake. Another lake, known as Reelfoot Lake, came into existence in Obion County, Tennessee. This lake is 20 miles long and 7 broad, and the fisherman's boat floats to-day over the submerged tops of cypress trees.

In addition to sections of country which were depressed and submerged, an area to the east of the "sunk country" and of some 20 miles average diameter, was elevated into a low dome 20 or 25 feet above the average level of the alluvial plain of the Mississippi. The evidence of this may be seen to-day by the traveler along the lower Mississippi, since this dome is the unique elevation of the

flood plain of the river between the mouth of the Ohio and the Gulf. Its surface reveals the same meanders, bayou lakes, and other topographical peculiarities which belong to the present flood plain of the river. Its sudden elevation athwart the course of the Mississippi during the earthquake may account for the reversal of the current which has been described by so many observers.

[...]r shocks. The after shocks of the New Madrid earthquake were of very frequent occurrence throughout many years, and may be said to have continued to the present day. A year scarcely passes without these subterranean rumblings, rattling of dishes in houses, suddenly increased flow of the springs and wells within the district, sinking of the ground with consequent changes in the areas of lakes, as well as the formation of small fissures in the surface of the ground. This quite remarkable continuance of the after shocks seems to be explained by the settling of the ground in consequence of the removal of sand from below through the agency of springs and wells.

[...] Owens [...]y [...]thquake [...]872. One of the most scientific, though brief, early accounts of a great earthquake is by the American geologist Gilbert, and relates to a disturbance which affected especially the Owens valley near the eastern base of the Sierra Nevada Mountains, which form the western border of the Great Basin of the United States.

[...]king of [...] ground [...]strips. The Owens valley earthquake accompanied the sinking of the ground in strips so as to produce fault scarps, the principal one of which followed the base of the foot slope of the mountains, and had in places a height of about twenty feet. Where it was highest there was a parallel fault ten feet in height which faced in the opposite direction. In the vicinity were other similar faults running nearly parallel and faced in the same direction

(see p. 78 and Figs. 64 and 69). The length of the main fault was about forty miles. Various tracts of land were sunk below their previous positions, and several thousand acres was not only lowered bodily but shifted northward by about fifteen feet. Many springs disappeared through the new fissures opened.

Block adjustment of the earth at Lone Pine.

The surface changes of the crust were greatest at the junction of different geological formations. In the vicinity of Lone Pine and elsewhere the newly formed fissures formed a network, within the meshes of which the sections of ground were either raised or lowered, so as to become quite impassable. At Big Pine was a series of extensive fissures traceable for several miles. Here an area of ground 200 to 300 feet wide was sunk in places to a depth of 20 feet or more, leaving vertical walls on

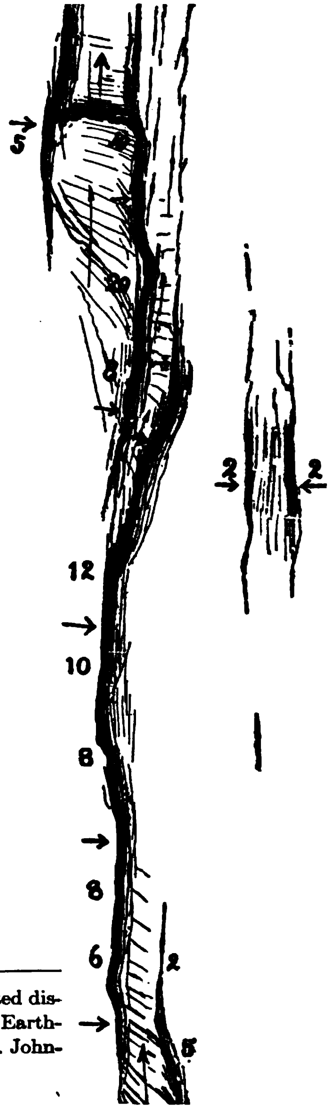

FIG. 64.—Map of a portion of the faulted district in the Owens valley, California. Earthquake of 1872 (from a map by W. D. Johnson, June, 1907).

PLATE XVI.

A. Small lake formed through obstruction of drainage by a fault which was in part formed during an earlier earthquake.

B. Alignment of small craterlets along an earthquake fissure.

VIEWS ILLUSTRATING SOME GEOLOGICAL CHANGES DURING THE EARTHQUAKE IN THE OWENS VALLEY, CALIFORNIA, ON MARCH 26, 1872. (After photographs by W. D. Johnson.)

either side. This depression, becoming filled with water, made a pond a third of a mile in length. On the road from Bend City to Independence, a north-south fissure crossed the road, and the westerly portion was seen to be carried eighteen feet to the south.

In Lone Lake a wave resulted from recession of the water from the banks, and is reported to have appeared as a perpendicular wall running lengthwise of the lake in a north and south direction. There was but a single violent shock, which was accompanied by loud rumbling, and all the above described changes were accomplished within a few seconds. After shocks and tremors continued for two months.

rthquake ng the lantic board 1886.

It sometimes happens that a region of relatively high seismicity is for decades or even centuries not visited by shocks of really catastrophic violence. So much the more terrifying is the disillusionment from the supposed stability of the earth pedestal when a genuine catastrophe arrives. Before the eventful August 31, 1886, few, if any, of the inhabitants of the quiet city of Charleston, S. C., had the slightest idea that they stood in danger from earthquakes.

phe- mena in rleston.

Preceded by two light shocks which were noted in the vicinity upon August 27th and 28th, the destructive disturbance of the Charleston earthquake came at 9.50 P.M. on the evening of the 31st, when the greater number of the inhabitants of the city were retiring to their beds. With earthquakes of the first order of intensity the most dangerous of all places is beneath a heavy roof. The shocks of the Charleston earthquake, however, appear to have been, for the most part, less violent, and the greatest danger arose from the hurling of the bricks of chimneys into the street. The number of chimneys thus thrown off above the roofs was counted and

found to be about 14,000. Comparatively few roofs or walls were thrown down, and these were in more or less definite lanes within the city. The destructive shocks lasted little more than half a minute, and the period of greatest destruction was comprised in the first twenty seconds. The noise which accompanied the shocks was likened by some to the rumblings of a near train of cars in motion, by others to the clatter of omnibuses over a roughly paved street, and by others to the escape of steam from a boiler. This was followed by a thumping and beating of the earth beneath the houses. Hastily emerging from their homes into the street, the people saw the air filled with a fine white dust, the comminuted mortar from the ruined masonry, especially of the chimneys.

Sand craters and their distribution.

One of the most interesting of the phenomena in connection with this earthquake left its records in the large and numerous "craterlets" which were scattered over a large area of the Atlantic coastal plain. Of almost equal interest was the distribution of the damage to the tracks of the three railroads which leave the city of Charleston along different directions. Some of the craterlets, which were aligned along fissures, measured twenty feet in diameter; and the water, sand, etc., which gushed from them shot in some cases twenty feet into the air, as was conclusively proven by the mud which incased the limbs and foliage of the overhanging trees.

The damage to railway tracks.

Upon the railway tracks, at widely varying distances from each other, points of exceptional wrenching and displacement were found. Not only were the fish-plates which connect the rails broken and the joints opened in some localities, but the rails themselves were elsewhere found to have been thrown into sharp kinks, or buckled (see Fig. 65). The positions

A. Sunken strip of country crossed by a flume which measures the change in level.

B. Retreating faults. The fault on which the man is standing disappears as it approaches the left foreground. A parallel fault begins to the right in the middle distance and increases its displacement as it approaches the right foreground.

VIEWS ILLUSTRATING SOME GEOLOGICAL CHANGES DURING THE EARTHQUAKE IN THE OWENS VALLEY, CALIFORNIA, ON MARCH 26, 1872. (After photographs by W. D. Johnson.)

where special wrenching or kinking of the tracks occurred correspond quite exactly to the intersection with the tracks of lines of fissures marked out by rows of

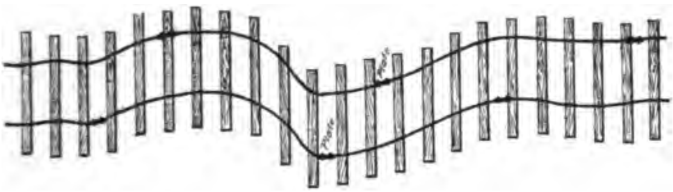

FIG. 65.—Example of the kinks in the railway tracks near Charleston produced during the earthquake of 1886.

craterlets. We have here, therefore, the evidence that the ground has been laterally shifted in large blocks, and in some instances in a vertical direction as well (see p. 31).

While the considerable damage at the time of the earthquake was very largely restricted to an area of some 600 square miles lying to the west and northwest of Charleston, the shocks were felt at many distant points throughout the greater portion of the eastern United States. They were, however, especially distinct in places which are ranged upon a nearly straight line connecting the national capital with the city of Boston—a line generally recognized to mark the course of a plane of fracture in the earth's crust. Smaller adjustments appear to have taken place throughout the larger field of the light disturbance.

[...]e Sonora [...]rthquake [...]f 1887. To the greater number of persons earthquakes take rank according to their destruction of human life and property. The scientific study of earthquakes necessitates, however, the use of a wholly different standard of measurement. The so-called Sonora earthquake, which occurred upon May 3, 1887, measured in terms of the area affected by it and by the magnitude of

the geological changes which accompanied it, must take rank among the really great earthquakes of the world, even though scarcely chronicled at the time in the world's centers of culture. This is accounted for by the fact that the region affected was a great expanse of desert, sparsely peopled by Indians and having only a few scattered ranches and mining camps. More than one-half of Mexico and two-thirds of New Mexico and Arizona felt the shocks.

Elevation of the Sierra Teras. The zone of the greatest destruction from the Sonora earthquake appears to have been in the province of Sonora upon the northern border of Old Mexico. Here a range of mountains, the Sierra Teras, was uplifted between faults which opened upon either side. The largest amount of vertical displacement upon either of these faults was about twenty feet, and it varied from this amount to zero. Though located for the most part at the base of the range, these faults occasionally cut across rocky spurs and cañons. Millions of cubic feet of rock were thrown down from the slopes into the cañons and water courses, and cliffs of compact rock were shattered and split as though by a charge of giant powder. Though the mountains were, as a whole, uplifted, with respect to the land upon either side, this was not the case throughout, as, for example, for some distances along the western fault the displacement had occurred in the opposite direction. In following the crack the displacement seemed at times to have wholly disappeared, but would again become apparent and allow of further tracing.

Smaller adjustments in the neighborhood. Hundreds of smaller fissures opened in the country surrounding the range. On these fissures, which sometimes divided the ground into strips, the land was bodily uplifted from one to two feet (see Fig. 66). As described by many observers, the cracks in

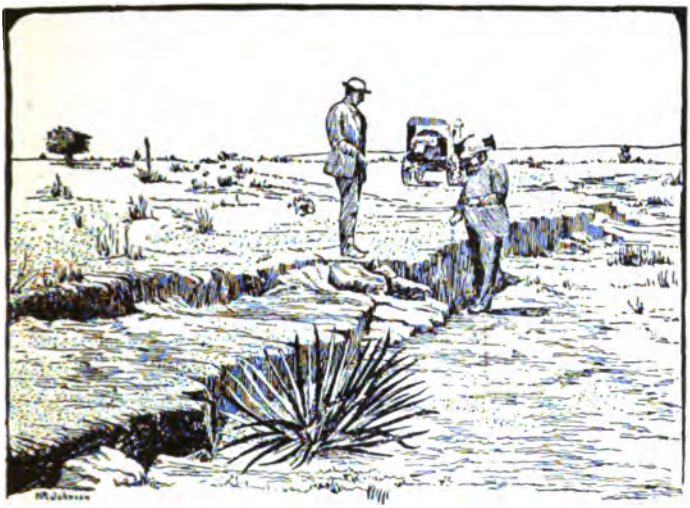

FIG. 66.—Small earthquake faults in the Arizona desert (after Branner).

the Sulphur Spring valley discharged large quantities of water when they first opened. The wells also in the vicinity overflowed and were left partially filled with sand.

rrange-nt of ater urses.

Along nearly all of the cracks crater-like depressions two feet or more in diameter were arranged, from which the sand and water gushed. Such areas were surrounded by zones which had been depressed and were often covered by blankets of fresh sand a foot or more in depth. The Bavispe River, a tributary of the Yaqui, thus came to be in time of excessive drought swollen to the volume which it usually had in the rainy season. The bed of every water course within the San Bernardino valley changed level with reference to the plain by an amount which ranged from six inches in some instances to two feet in others.

The first effect of the shocks upon the underground water was a welling out in large quantities from cracks and craters in the surface. This ceased, however, so soon as the quaking was over; and the principal swelling of the rivers, though it antedated the arrival of the rains, succeeded to a period of drying up of springs which followed immediately after the initial shocks of the earthquake. The settlement of the surrounding valleys when the Teras range was uplifted, probably first squeezed out the water at that time within the joints of the underlying rock and overlying material, which latter is usually to be obtained at ordinary times by digging a few feet below the surface. The later effects, which began and ended gradually, must be ascribed to later and smaller adjustments of the blocks of crust, the most marked manifestations of which were the frequent light after shocks and the much more numerous subterranean rumblings, which seemed to come particularly from the neighboring range of mountains.

The forest fires. The Sonora earthquake appears to have been connected with the starting of numerous forest fires, due probably, in some cases, to sparks emitted from flinty rock in connection with the great landslides. In other instances they may have been started by the friction of fault walls upon each other. Cinders and burned branches of trees were found overhanging the faults in some cases.

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CHAPTER XI

GREAT EARTHQUAKES WITHIN THE TERRITORY OF THE UNITED STATES (*Concluded*)

THERE seems to be a rather general impression that the years 1906–7 have brought more than their share of heavy earthquakes; and a certain recurrence of periods of greater earthquake intensity does seem to be indicated by the records, especially in Japan. Still, the prominence which the earthquakes in 1906 and 1907 have taken in the public eye, is largely to be accounted for by the fact that they have occurred so often upon the land areas, and especially in thickly settled communities in close touch with the world's pulse. Much larger disturbances upon the floor of the ocean, or heavy earthquakes in South America, or in the South Seas, would have passed without notice.

Earthquake of Yakutat Bay, Alaska, in 1899.

How many persons are aware that in the month of September, 1899, an earthquake of the first order of intensity profoundly modified the face of the country over a large but as yet undetermined area in southern Alaska? A fanciful account of this earthquake did, it is true, appear in a San Francisco newspaper, not a fortnight after the first shocks were felt; but this is of interest as a note rescued from oblivion, and not because it led to a dissemination of scientific accounts of the disturbance. That some remark-

A. Sea beach uplifted during the earthquake so as to produce a wall at the present shore.

B. Forest at an altitude of forty feet above the sea destroyed by earthquake waterwaves. Landslips which occurred during the earthquake appear upon the mountain face.

VIEWS ILLUSTRATING SOME GEOLOGICAL CHANGES DURING THE EARTHQUAKE ABOUT YAKUTAT BAY, ALASKA. (After photographs by Tarr and Martin.)

able changes had taken place in southern Alaska was known when in 1900, and in succeeding seasons, the tourist steamers to Alaska found the entrance to Glacier Bay choked by bergs from the fractured glaciers. It was not, however, until 1905, when two geologists visited Yakutat Bay, that any adequate conception of what had occurred was obtained, and the published report of these gentlemen reached the scientific world nearly seven years after the earthquake.

Despite the long delay in securing the facts about the Yakutat Bay earthquake of 1899, it may be doubted if any earthquake which has been studied has so clearly revealed its nature and cause. In large measure this is to be explained by the fact that the district studied is intersected by a series of deep fjords which allow all changes in level of the land areas to be directly measured from a constant datum plane—the level of the sea (Fig. 67).

a beaches vated.

The region about Yakutat Bay, where the studies of this earthquake were made, showed upon examination that great sections of the country had behaved like individuals, and had been some elevated and some depressed, as though they were great blocks which had slipped upward or downward past their neighbors. How much each raised block had been elevated, it was in many cases possible to determine by measurement of the altitude above sea of the now abandoned shore lines. These elevated shore lines gave the appearance that the sea had been lowered (see Plate XVIII, *A*) by amounts different at different places, but upon the average between 5 and 12 feet, and in extreme cases 30 and even 47 feet. Barnacles were found still attached to the rocks of the cliffs above the now abandoned beaches, and these served as a guide in distinguishing the later from still earlier uplifts of the coast.

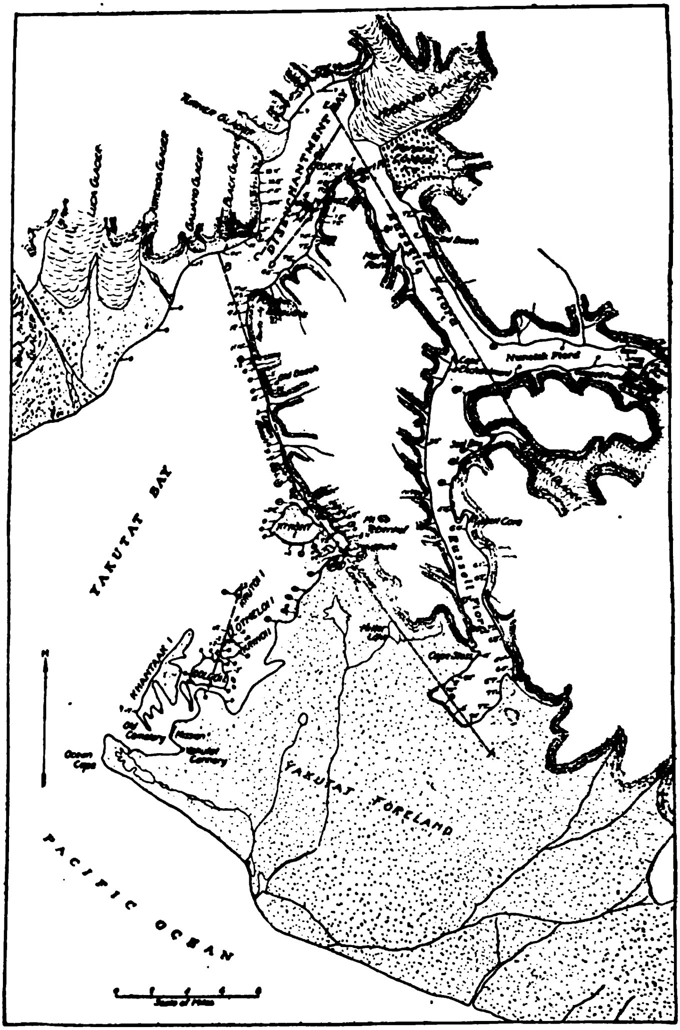

Fig. 67.—Sketch map of a portion of the region affected by the Alaskan earthquake of September, 1899 (after Tarr and Martin). The full and dotted lines indicate the known and the probable positions of the fissures on which movement occurred at the time of the earthquake.

...lts and ...ures. The shores of the fjords and the inlets of the Yakutat Bay district are intersected by a network of fissures on which, prior to the disturbance of 1899, large and small displacements are known to have taken place. To judge from the positions of the beaches, the fissures which were the seat of the larger movements during the late earthquake are concealed beneath the fjords and the inlets themselves, since the sections of land which they outline were moved as individual blocks. Smaller adjustments of portions of these larger blocks upon each other are recorded in newly formed surface faults, between which the land was moved in strips either upward or downward (see Plate XIX, *A* and *B*).

The subdivisions of the larger crust blocks into smaller units which, in their turn, have undergone adjustments of level, is almost as clearly indicated by the sudden variations in the displacements which have occurred upon the main fissures. As will be seen from Fig. 68, the relative movement upward or downward seems to have been localized within sections of subequal length, and these divisions are separated at the intersections of valleys by which the mountain mass is divided. These valleys would thus appear to follow the lines of ancient fissures, which mark out the boundaries of blocks moved individually at the time of the earthquake. A somewhat similar condition was observed along the course of the great Chedrang fault which originated during the Indian earthquake of 1897 (see Fig. 60, p. 163).

The areas about Yakutat Bay which were depressed at the time of the earthquake are many of them now submerged, and hence are not so accessible for purposes of measurement. Where the depression has been insufficient to carry them below sea level we are without the necessary

data to fix their former elevation, but the facts are in some cases beyond question. Wherever the shore has by the

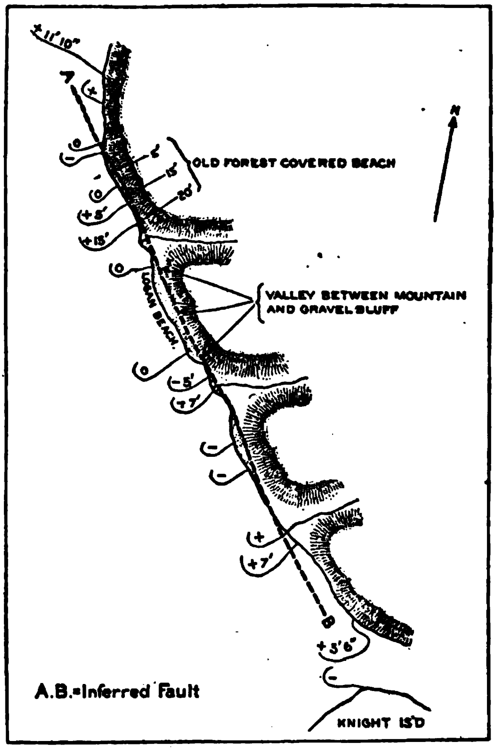

FIG. 68.—Sketch map setting forth the variations in the displacements along a main fault on the east side of Yakutat Bay (after Tarr and Martin). The minus sign indicates depression which occurred at the time of the earthquake, the plus sign elevation, and a zero sign a stationary condition.

movement been brought a short distance only below sea level, the sea has invaded the forest, the trees of which were

PLATE XIX.

A. Newly formed fissures of different parallel series.

B. Land moved in strips between parallel faults.

Views Illustrating some Geological Changes during the Earthquake about Yakutat Bay, Alaska. (After photographs by Tarr and Martin.)

found dying as the result of the salt water in which their roots were bathed. In such areas, also, the rank beach grass was gaining a foothold back in the forested areas.

ew islands rmed.

No soundings have been made which would indicate how great have been the changes in level upon the sea bottom, but the appearance of a number of new reefs and islands clearly reveals the fact that movements have there occurred. One of the newly formed islands is 450 feet long and about 75 feet broad, and apparently rises from deep water. Elsewhere elongated reefs which before the earthquake were visible at low tide only, now project above water at high tide. These reefs and islands are generally several times as long as they are wide, and extend parallel to the mountain range and to the fault along its front.

ecords of rlier rthquakes n the istrict.

The elevation of the reefs into low islands suggests that the latest movement represents but a single stage in a progressive series of upward, jolting displacements, each of which was accompanied by its resulting earthquake. Such a condition seems to be generally characteristic of successive movements in connection with earthquakes in other districts, and it is supported by evidence from the region under discussion. Upon the shore of Russell Fjord are found three beaches ranged one above the other like successive steps (Fig. 69). The lowest of these is the beach which has formed since the earthquake of 1899. The middle beach of the series, which is here nine feet higher, is the one which was abandoned during the sudden uplift of 1899, while the uppermost is four feet higher still and dates from an earlier uplift of unknown date. Inasmuch, however, as this uppermost beach is covered by a dense thicket of alders, it must have been above the reach of the waves for at least twenty-five years.

Still other and higher abandoned shore lines are found elsewhere in the district, which from the evidence of trees growing upon them must have been given their first ele-

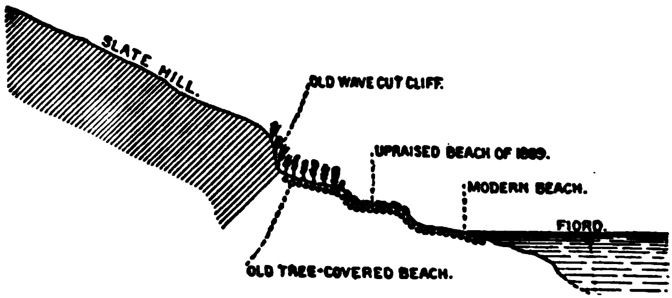

Fig. 69.—Profile of the shore of Russell Fjord opposite Marble Point. Three beaches in succession preserve the record of two uplifts of the country which amount to four and nine feet respectively (after Tarr and Martin).

vation fully seventy-five years ago. The records of still earlier uplifts of the coast have here been obliterated through the action of the glaciers.

Destruction by sea waves. When sudden movements of the crust affect a portion of the sea floor, they seem generally to be accompanied by disturbances of the sea which have been erroneously called "tidal waves." The sea usually withdraws from the land and later returns in a great wave which carries destruction before it and washes objects from the shore far back upon the land. During the earthquake around Yakutat Bay a party of prospectors were in camp upon the shore of Russell Fjord, and were, together with their entire equipment, washed by the sea wave which followed far back upon the shore. A forest forty feet above the level of the bay was by this sea wave leveled as far back as the steep mountain front, so that the twisted and

fallen trunks made a scene of utter confusion (see Plate XVIII, *B*).

fornia thquake 906.

The California earthquake of April 18, 1906, is likely to be memorable, because the value of the property destroyed reached astounding proportions, and because it appears to have first aroused the American nation to the danger from earthquakes. The loss of life, mainly in the city of San Francisco, was but a tithe of what it would have been had the shocks come at a later hour when men were at their places of business and the children crowded in the poorly constructed school buildings of the city. As it was, the greatest loss was due to the fire started by the earthquake, which was soon without control because the water mains had been snapped by the earth movement.

As has so frequently been true, the heavy shocks came without warning, and in this instance at 5.12 o'clock on the morning of April 18th. They continued about a minute and graded into lighter disturbances which were felt until evening, and, in fact, for many days thereafter, though they gradually faded away in intensity.

principal thquake of Cali- nia.

The State of California is crossed by a long and nearly straight furrow, which cuts diagonally athwart the coast ranges and is directed about N. 35° W. (Fig. 70). This great rift in the surface has been traced for about 400 miles, from Punta Arenas on the north to the vicinity of Mount Pinos in Ventura County upon the south. This strong lineament in the surface is explained by an "earthquake crack"—a zone of displacement in the crust—and its course is marked out by long and narrow "sags" in the surface of the ground, or by elongated lakes which sometimes have no outlet and contain saline waters. Above such lakes the

slopes rise in precipitous walls or scarps, sometimes on one and at other times on both sides. Either the same or a

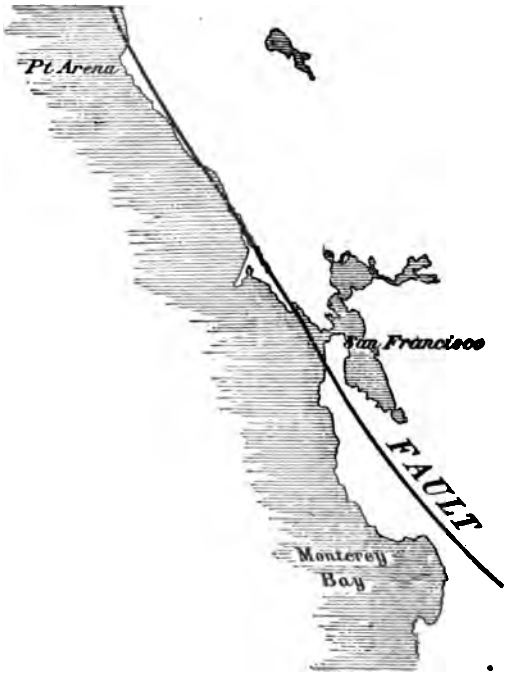

FIG. 70.—Map of a portion of the great California rift on which renewed movement occurred April 18, 1906 (after Omori).

near-lying crack crosses the Mohave Desert as a sharp ridge not unlike a gigantic upturned furrow.

Movements which have occurred upon this great earthquake crack extend back to the Glacial Period, and all of the numerous movements have doubtless been accompanied by earthquakes, the intensities of which were in each case proportional to the amounts of the slips.

A. Road displaced laterally about twelve feet on line of the great rift near the head of Tomales Bay.

B. Mole-hill effect produced above a fault north of Bolinas.

VIEWS ILLUSTRATING SOME GEOLOGICAL CHANGES DURING THE EARTHQUAKE IN CALIFORNIA ON APRIL 18, 1906. (After photographs by Fairbanks.)

ies of movement 1906.

Examination of the great rift shows that movement occurred upon it during the earthquake for the distance of 185 miles which it has been followed since the disturbance (Plate VII). This movement took place upon essentially vertical planes, and was in part a lateral shift along the fissure, and in part an uplift of the land upon the one side with reference to that upon the other. The area southwest of the fault was generally shifted northwestward by amounts ranging from a few feet to as much as twenty feet. At Tomales Bay, north from San Francisco, the displacement is, however, in the reverse direction and measures about twenty feet. The vertical movements at the surface appear in no case to have exceeded four feet, and the uplifted side was generally the southwestern. This is, however, not universal, for in some places the uplift was upon the eastern side of the fault by as much as two feet.

No large city is located upon the course of the rift, but the changes in the earth's surface indicate that the shocks were greatest in its immediate vicinity, and graded away somewhat rapidly in directions perpendicular to it.

The line of greatest destruction from the earthquake followed a remarkably straight lineament which varied but a few degrees from the direction of the rift line, though it was located some distance farther to the northeast. Its course was marked out by the straight eastern shore of the Bay of San Francisco and the valleys which extend it to the northwest and southeast. The towns which, relative to their extent and population, received the greatest damage from the shock, were Santa Rosa, Healdsburg, Agnews, and San José. Oakland, Cloverdale, and Ukiah were also much damaged, and far to the north Petrolia and Ferndale suffered heavily. Geological changes in the

surface of the ground, at those places where the absence of towns had left no record in damaged property, were es-

FIG. 71.—Sketch map showing the lines on the earth's surface which were most disturbed at the time of the California earthquake of 1906.

pecially marked on the Punta Delgada, where a newly made fault at the surface of the ground was discovered;

on the north side of Suisun Bay, some thirty miles northeast of San Francisco, where the tracks of the Southern Pacific railway subsided several feet; at Alviso at the south end of the Bay of San Francisco, where a similar subsidence was reported; and along the Salinas and Pajaro River valleys, which open from the Bay of Monterey. The sketch map of Fig. 71 indicates the position of these lineaments, the most noteworthy of which is that which aligns the towns of San José, Agnews, and Alviso; follows the straight eastern shore of the Bay of San Francisco past Oakland and the lower part of Berkeley; and is extended up the Santa Rosa valley, past Santa Rosa to Healdsburg, Cloverdale, and Ukiah. Still farther, a nearly parallel lineament is extended to the fault at the Punta Delgada and the damaged town of Petrolia. Along all these lines damage was greatest over loose foundations, which transform earthquake waves into others of greater destructiveness (greater amplitude).

e damage San rancisco.

The city of San Francisco is situated over none of the lines of danger which have been specially mentioned above. It is known, however, to be crossed by a fault line which runs in a northwest-southeast direction from the Golden Gate to a point upon its southeast shore. It was either over or near to this line that the Valencia Hotel collapsed and that the fissures appeared in the ground at the corner of Valencia and Eighteenth streets. The main destruction to the city from the earthquake was in a lane roughly along the direction of Market Street, which extends northeast and southwest. The extension of this line corresponds roughly to the straight northwestern coast of Suisun Bay, where the railway tracks sank in the marsh at the time of the earthquake. It was in a zone about this line as an axis that the de-

struction from the Vacaville earthquake of April 19, 1892, was localized.

In addition to the fissures which opened in the streets of San Francisco, trough-like depressions of the ground indicate that small movements in the nature of adjustments occurred upon many planes besides the large ones to which attention has already been called. Professor Branner counted in the distance of one mile no less than 345 fissures of considerable size running in many directions. Along the faults which bound the trough-like depression within the city of San Francisco, a lateral displacement of ten feet was measured (see Plate VI, *B*). Buildings which had been well constructed appear in some cases to have remained almost stationary while the ground slid along beneath them, carrying with it the foundations. One instance of this kind in which the house was practically uninjured showed the underpinning projecting four feet beyond the house walls (see Plate VII, *A*). It is a well-known fact that the district of California within which the earthquake was mainly felt is intersected by long northwest and southeast faults, which in turn are traversed by many minor dislocations such as would be necessary to account for the local effects in San Francisco (see Plates V, *A*, VI, VII, and XX).

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CHAPTER XII

EARTHQUAKE DANGER SPOTS WITHIN THE UNITED STATES

Principal seismic areas. THE better defined earthquake provinces of the United States have been mapped by the eminent French seismologist, De Montessus de Ballore, upon the basis of records from past disturbances; for it is a well-recognized fact that where earthquakes have been they will be again. It is, however, by no means necessary to seismicity within a province that earthquakes of catastrophic violence should have been recorded from it. Seismicity takes account of the light as well as the heavy shocks of earthquakes, and thus involves the frequency as well as the intensity of the disturbances.

From the New England region no earthquake of destructive violence has been recorded, but it is none the less a province of rather high seismicity and one which is likely at any time to be visited by a genuine disaster from this cause. The same statements apply with almost equal force for the entire Atlantic seaboard from Nova Scotia to Georgia. Other districts of the national domain which are especially likely to be disturbed by earthquakes are the central Mississippi valley, the valley of the St. Lawrence, and large areas not as yet well determined in the Great Basin and Pacific coast regions of the Western States.

Over the border in Old Mexico is a large region which has been frequently tormented by heavy earthquakes.

It must not be supposed that within each of the provinces especially mentioned above as subject to earthquakes the danger from this cause is equally great throughout. From the preceding chapters we have learned that destructive earthquakes result either from movements on new fracture planes, or from adjustments which take place among blocks of the earth's crust, and are directly due to the shocks set up in the marginal portions of these blocks during their slips along the steep fracture planes which separate them. The same fracture planes are thus the seats of successive movements, each of which is the cause of a separate shock of earthquake.

Certain of the faults which exist within each earthquake province have been brought to light by the geological study of the district. Others are indicated by the notably rectilinear features in the relief—the lineaments; but by far the most reliable method of discovering them is, as we have seen, to note the distribution of damage from earthquakes which have visited the province in the past. Structures which have been shaken by the lighter quakes would probably have been thrown down by heavier ones, and it has been found that the studies of the lighter shocks are, on the whole, the more valuable for accurately locating the faults.

The "fall line" of the Atlantic seaboard.

For the Atlantic coast region it has been remarked that a number of earthquakes have each shown a noteworthy tendency to search out the line of cities which are ranged upon a great circle of the earth and extend from the national capital to the city of Boston (see Fig. 72). Upon this fracture line, generally known as the "fall line" from the fact that rapids

mark its intersection with the rivers flowing toward the sea, are aligned Boston, New Haven, New York, Trenton, Philadelphia, Wilmington, Baltimore, and Washington, besides a large number of smaller places. The earthquakes of May 18, 1729, August 10, 1884, and August 31, 1886, were all felt with special force along this line. It is not a pleasant thought, but perhaps so much the more a profitable one, to consider what would be the effect of a really catastrophic earthquake which was due to considerable adjustments of the earth blocks which meet on the fall line.

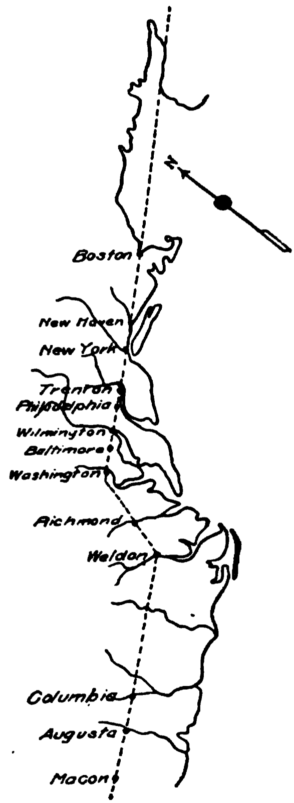

Fig. 72.—Sketch map to show the position of the "fall line" along the Atlantic seaboard.

The central New England coast line.

For the New England province, some of the lines on which there is greatest liability to movement have been indicated in Fig. 30 (p. 87) as well as upon Fig. 44 (p. 114). Much the most important of these lines follows the straight and central New England coast line with its extensions, so as to include Point Judith, Greenwich, Boston, Newburyport, Portsmouth, and Portland. The fall line already referred to corresponds in position to the southwestern Connecticut coast line, and is extended across southern

New England so as to intersect the lower Connecticut River at East Haddam. The straight course of the Hudson River, extended in Lake Champlain, and the straight Connecticut River above Hartford, are likewise lines of special danger from earthquake. The St. Lawrence valley is no less clearly marked out as a danger zone through the records of past earthquakes. An earthquake of catastrophic violence visited the entire explored territory of New France on February 5, 1663 (see Appendix F).

Earthquake prominence of East Haddam and Newburyport.

Within the specially marked earthquake provinces of the United States, it has been seen that danger from earthquakes is greatest along the course of certain lines of fracture within the crust—the boundaries of earth blocks. Further, danger is not the same at all the points along these lines, being greatest where they are intersected by similar lines of fracture—it is greatest at the corners of the blocks. Thus we may explain the earthquake prominence of certain villages, such, for example, as East Haddam, Conn., and Newburyport, Mass. The first mentioned locality is, as already stated, located where the fall line intersects the gorge of the lower Connecticut River, itself a strongly marked lineament. Ever since its settlement this town has been subject to frequent light earthquakes, which have, for the most part, not been felt elsewhere in the neighborhood. Even when shocks have not been felt, subterranean rumblings have been frequent. That the instability of East Haddam dates from a much earlier period is clearly shown by the name *Morehemoodus* applied to the former Indian village upon its site, since this term is translated the Place of Noises.

The early colonial and later records of Massachusetts may be cited to show that the earthquake history of New-

buryport differs only in degree from that of East Haddam. Sensible earthquakes, including some of considerable violence, have been often reported from this place.

The danger spots of the lower Mississippi valley.

One of the greatest earthquakes which has ever been reported from the territory of the United States has become known as the New Madrid earthquake, and occurred in 1811 (see p. 174). The area chiefly affected by the shocks lies in the alluvial plain of the Mississippi River. With hardly an important interruption, light shocks have been felt at frequent intervals even to the present day, which unique phenomenon, as we have already seen, seems to call for a special explanation. The zone of greatest interest and importance is that which follows the course of the river itself between the cities of Cairo and Memphis.

The localization of danger on the Pacific coast.

The Great Basin region of the United States and the Pacific coast have alike been visited by many earthquakes, among them a considerable number of great violence. Within the first-mentioned region the shocks have been localized upon the borders of the basin, and, so far as recorded, either at the western base of the Wasatch range of mountains in Utah, at the eastern base of the Sierra Nevadas, in California and Nevada, or in Arizona and New Mexico toward the international boundary. These margins of the Great Basin have long been recognized as zones of faulting, and it is found that the latest movements upon them are so recent that living trees have been disturbed and vegetation has not started upon the exposed fracture surfaces. Because of the sparse population of the district and the meager records which have been preserved, these slips upon the fault planes have not been individually connected with particular earthquakes, but their relationship is undoubted.

To the westward of the Sierras the danger points from earthquakes acquire a larger human interest because of the

Fig. 73.—Map showing the more important fault lines of the San Francisco peninsula (after Ransome).

greater adaptability of the country to human habitation and its larger occupation. The disaster of April 18, 1906, the

damage from which affected particularly the city of San Francisco, is too fresh in mind to make it necessary to lay special stress upon the dangers from earthquakes about the Bay of San Francisco. The danger in that district, is, however, by no means restricted to the shores of the harbor; and, in fact, the disturbance of April 18th was greatest along two lines which pass some distance to the eastward and westward of the city of San Francisco. These lines of more intense shocks are indicated upon the sketch map of Fig. 71 (p. 198).

Other lines of weakness are many, and for the San Francisco peninsula the more important ones are shown by the series of faults mapped in Fig. 73.

The materials for the construction of a rough earthquake map of the Pacific slope are now largely at hand in the form of a fairly complete record of the later earthquakes within the district, supplemented as these are by studies of its structural geology (see Fig. 40, p. 107).

Where an earthquake has caused such destruction within a populous community as was the case in the recent disaster at San Francisco, it is possible to determine with considerable accuracy the lines of special danger from shocks. Professor Milne has called attention to the way in which the sensations of different persons all within the same small area illustrate this. One observer describes the shock as sharp and coming from the north, while his neighbor states that it was gentle and came from the east or west. In another part of the same city several observers report that neither they nor their families felt any shock whatever. A shock sufficiently strong to cause the members of a club in Tokyo to take refuge in the street was not felt in houses three quarters of a mile distant. A gentleman in Tokyo, by making inquiries concerning

another of the local earthquakes, found that it had been felt only along a certain line passing through the city. The first shocks of the great Calabrian earthquake of 1783 threw down all the houses along a single street of the city of Monteleone. On August 8, 1905, this city was again visited by a destructive earthquake, and the structures along the same street were again leveled with the ground, so as to produce a lane of destruction as clearly marked out as the track of a tornado. Before rebuilding a city which has been partially destroyed by earthquake, a map should be prepared to set forth the lines of greatest damage from the shocks. Over these lines of special danger buildings should on no account be erected, but in their place broad streets and public parks should be laid out. To proceed in any other manner is to court destruction.

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CHAPTER XIII

LOCAL UNFELT EARTH TREMORS

gradual
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dysisms).

THAT there are progressive vertical movements of sections of the earth's crust so slow as to be imperceptible except when measured over long periods of time, and that these movements occasion the most important of the changes in level at the surface, is the fundamental conception upon which modern geology is founded. To one familiar with the facts no argument is needed to show that such movements take place. Some coasts of the sea, as, for example, those of Maine and Scandinavia, show in their deep embayments (fjords), that the sea has flowed up the rivers as the land has sunk, and has thus drowned the outlets. On the other hand, the relatively even shore line and the level surface of other coasts, as, for example, the peninsula of Florida, show no less clearly that the sea bottom has there been laid bare through a retirement of the water from the land. The only conclusion warranted by either of the above-described conditions is, that change of level of the land relative to the sea has occurred, and that this change has extended over long periods of time.

At greater distances from the ocean a like conclusion regarding adjustment of level within neighboring sections of the earth's surface is arrived at in a different way. In a number of different countries it has been remarked that

certain houses, churches, or even villages, which had beforetime been hidden from definite points of observation, have after the lapse of years come into view. Other places, before visible, have disappeared below the horizon in the course of but a few decades. Instances of this kind have been furnished by the Jura province on the border of Switzerland, by Italy, and by Spain;—but all, it should be noted, countries of noteworthy seismicity. Such changes show quite as conclusively that an adjustment of the crust has taken place, as do the elevations or subsidences of land recorded at the borders of the sea. The name *bradysisms* has been applied to all such adjustments recorded in the slow changes of level of definite portions of the earth's surface.

Mysterious sounds not accompanied by sensible quakes (brontidi).

In several countries mysterious rumblings have been heard at intervals, but generally at night, when other sounds are hushed. In the past, such rumblings have been supposed to be due either to the distant roar of the surf upon the seashore, to loud reports from the firing of heavy artillery, to the heraldings of approaching thunder storms, to blasting in mines, or to some other similar cause. Among the peasantry these popular explanations are reflected in the names by which the sounds have come to be known. Thus, in India they have been designated *Barisal*[1] *guns,* in Mexico *bramidos* (bellowings), in Holland *Mistpoeffers* (fog dissipators), and in Italy *balza* (cliff, referring to landslips), *marina* (seashore), or *Rombo* (humming sound). Because of its peculiar sounds the Indian village which once occupied the site of East Haddam, Conn., was called *Morehemoodus,* or the Place of Noises.[2] In England such

[1] Barisal is the name of a town at the mouth of the Ganges.
[2] See p. 205.

rumblings have been often heard in Lancashire along the course of the great Craven faults.

One of the earliest reports upon such phenomena was made in 1845 by von Humboldt, who in his "Cosmos" tells us of the *Bramidos* heard at Guanaxuato in Old Mexico on January 9, 1784, and for more than a month thereafter. The effect was of heavy thunder storms which, instead of being above in the atmosphere, were under the feet of the inhabitants. Slowly rolling thunder alternated with sharp thunder strokes. Seized with terror, nearly all the inhabitants deserted the city, and only a few of the more courageous returned to protect the treasure of the silver mines. Neither upon the earth's surface nor in the deep mines (1,500 feet) was the slightest shock of earthquake perceptible. On the island of Meleda, in Dalmatia, similar sound phenomena have been heard with only the slightest sensible earth jars.

ation to sible kes.

Recent investigation has shown that these hitherto mysterious sounds are traceable neither to the roar of distant surf, to artillery practice, to mine explosion, nor to distant thunder; but that they are local, subterranean noises. Reports agree that the sounds are pitched deep and that they begin feebly, are rapidly reinforced in intensity, and as rapidly die out. They are more frequently heard at night or in the evening, when other sounds are hushed. The intervals separating them are notably irregular, and noises may be heard at frequent intervals throughout the day and night, and yet not be again perceived for weeks or months. Except for their lesser intensity, they cannot be distinguished from those sounds which generally accompany shocks of earthquake; and, in fact, the lighter earthquake after shocks fade in intensity until only the rumblings remain, which, in their

turn, diminish gradually in intensity until no longer audible. Such earth sounds, when not accompanied by sensible earthquakes, are likely to become known under the name *brontidi*, an Italian word which means " like thunder."

Relation of brontidi to lineaments and to known faults.

Considerable study is in some countries now being devoted to the interesting *brontidi*, and important facts have already been gleaned concerning them. It has been determined, for example, that they have been heard within some provinces only at

FIG. 74.—Sketch map of northern Calabria to show the location of villages in which the *brontidi* have been heard. The dotted lines show the courses of lineaments and probable fractures. The villages where the *brontidi* have been heard show a tendency to lie at the intersections of lineaments.

certain well-defined places, and these places bear a definite relation to the relief of the country. More definitely still, the sounds are heard in places which, in Calabria, at least, are arranged along lineaments of the surface, which probably mark the course of fractures within the crust (see Fig. 74).

It has been shown that the brontidi are more frequently heard when there are sensible earthquakes in not too distant provinces. This fact suggests that the distant earthquake serves as a fulminate to set off the charged system and bring about those slight adjustments that at the surface are perceptible only because of the low pitch of vibrations in the marginal portions of the earth sections displaced. They are the longitudinal frictional vibrations existing without the successional shocks characteristic of sensible earthquakes.

cause of ntidi. The identification of the brontidi with earthquake sounds, from which they differ only in intensity, and the observed gradation of earthquake after shocks into them, make it necessary to assume for both earthquakes and brontidi a single explanation. Just as the earthquakes have their origin in vibrations which are perceived as sensible shocks accompanied by heavy rumblings, which latter are induced in the marginal portions of earth blocks as they slide over each other; so the brontidi may be regarded as due to frictional vibrations which are of insufficient amplitude to disturb bodies at the surface of the ground. It has been suggested that the audibility of such sounds might be greatly extended through the use of the microphone, but the practicability of its use for this purpose has not as yet been adequately demonstrated.

The natural inference from the identification of bron-

tidi with feeble earthquakes is that the slow adjustment in level of sections of the earth's crust, the bradysisms, are only apparently and not really gradual; but are due to the cumulative effect of small adjustments many times repeated and irregularly distributed over a considerable lapse of time. An experimental verification of this inference would be of the greatest service to geology and would make necessary important modifications in views which have been generally held. It is known that following the heavy shocks of the great Assam earthquake of 1897, when the only seismic manifestations within the province were light after shocks and brontidi, adjustments of level sufficient to profoundly modify the face of the country were going on. This was proven in one instance, at least, by nailing boards to trees in such positions as to secure sights to definite landmarks and by making observations at frequent intervals along the lines of sight. A modification of this method has since been somewhat extensively used in Italy, where earthquakes are of quite frequent occurrence.

The photographic method of measuring bradysisms.

It has now been proposed in Italy to establish a number of stations at points favorable for viewing the surrounding country; as, for example, where several ranges of hills may be seen arranged *en échelon*. Cameras provided with powerful telephoto lenses, so as to greatly magnify the pictures taken, might be used to repeat at intervals throughout a long period, under as nearly as possible the same atmospheric conditions, the panoramic view from each station. These photographs, if dated and placed in correspondence with the dates when earthquakes have occurred or brontidi have been heard within the district, could hardly fail to furnish a decisive answer concerning the interrupted or uniform movement of the crust, provided measurable

changes were revealed by the photographs. As already stated, the inference from the study of earthquakes and brontidi is that the slow crustal adjustments are interrupted and not uniformly progressive in their nature.

[T]he ques[t]ionnaire [s]tudy of [b]rontidi.

The relation of brontidi to the fractures within the earth's crust was first learned in Calabria, where Professor Alippi went from village to village in order to make inquiries of the peasants. It was thus discovered that, whereas in certain villages the *marina,* as the peasants were accustomed to call the subterranean rumblings, were a matter of common knowledge, in other villages such sounds had apparently never been heard and the questions aroused no interest among the people.

There is in Italy a special royal bureau for the study of earth phenomena, and this bureau has hundreds of correspondents who are scattered throughout the peninsula and the neighboring islands ready to promptly report by telegraph whenever their district is visited by an earthquake. These correspondents have lately been employed to make inquiries concerning the distribution of brontidi, and an extended report has been published in 1907 which throws new light upon this interesting subject.

Emissions of fire-damp in coal mines.

The chief source of the danger in coal mines from contact with explosive carburetted hydrogen gas, known to the miners as fire-damp, arises from the fact that without warning the mine galleries become suddenly and mysteriously flooded by the gas which is forced into them through crevices in their walls. In France, England, Belgium, Germany, and Austria much treasure has been already expended for commissions to collect information and pursue experimentation, having in view the solution of this mystery of the sudden emissions

of fire-damp. As a result many lives and much property have been saved, but until quite recently the fruits of the labors of these commissions have been restricted to improved methods of constructing, lighting, and aërating the mine galleries.

Evidence is now being gathered which indicates that the emissions of fire-damp generally take place when the brontidi are heard in the vicinity, and shortly after moderately distant provinces have been visited by earthquakes. Should these preliminary studies be confirmed by more extended investigations, the mystery of fire-damp emissions would be thoroughly cleared up; for small settlements of sections of the earth's crust should be quite competent to expel gas from crevices into any open spaces which intersect them. In Belgium a Committee for the Study of the Correlations of Fire-damp Emissions and Earthquakes has already issued seven separate pamphlets.

Natural registration of bradysisms.

If bradysismic movements be spasmodic and occasional, it is probable that the surface layers of the earth's crust are moved independently in individual blocks in the same manner as they are by earthquakes, though here by amounts so small as to be generally imperceptible. It is the cumulative effect of such movements only which we may expect to be able to measure. Minor irregularities in the surface arising from this cause would in most regions fail of observation, either because of the unconsolidated nature of surface deposits, or because of the disintegrated character of the exposed rock surface and the rapidity with which it falls a prey to the tooth of time.

There is an exceptional combination of conditions which, in certain regions, favors the preservation of small displacements at the earth's surface. In the northeastern

part of the North American continent during the latest of geological periods—the yesterday of geology—a continental glacier or ice mantle moved southward over the disintegrated surface of the rocks, carrying with it all the loose material and planing everything down to a fluted and polished surface within the unweathered rock. Where the rock is of a resistant nature, as is here usually the case, or where it has been protected by the subsequent deposition of a thin layer of rock débris, the polished rock surfaces which have thus come into existence remain to-day as perfect almost as when the ice retired from the region.

Post-glacial faults.

That faults of small displacement and probable repeated movement in some localities interrupt the smooth ice-polished surfaces of the ledges, was known more than a half century ago. Little attention was, however, vouchsafed the observation at the time, but attention is again being directed to the subject. A considerable number of such localities have recently been discovered, chiefly in New England and in the neighboring portions of New Brunswick, Quebec, and New York. It is clear that such faults are not of general distribution, even in the areas favorable to their preservation, as they would otherwise have been more frequently observed. The arrangement of the localities already discovered suggests, moreover, that they may be restricted in their distribution to definite zones (see Fig. 30, p. 87).

Displacements of post-glacial faults distributed.

Where such post-glacial faults have been observed, the exposed surface of the ledges is seen to be faulted on steep planes (in all cases less than 30° from perpendicularity) which recur at frequent and fairly regular intervals. With few exceptions, also, the displacements have taken place in the same direction, so

that in passing across the ledges the ice-polished surface is seen to have been uplifted progressively into a series of steps, as is brought out by Fig. 75, and Plate XXI, *B*. The individual displacements seldom or never exceed five inches,

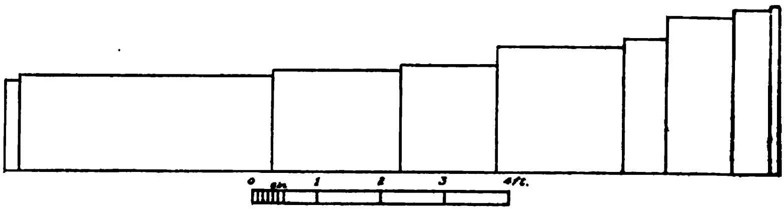

Fig. 75.—Diagram to illustrate the distribution of small post-glacial displacements (after Woodworth).

and are more frequently but a fraction of an inch. Though the individual displacements are small, the aggregate uplift represented by the entire width of an exposed rock ledge may be very considerable. Thus it was found by Matthew that at St. John, New Brunswick, within a distance of 11.6 feet nine small faults gave an aggregate measured displacement of 10 inches. In another instance, thirty faults distributed over a distance of 156 feet represented an aggregate measured displacement of 5.7 feet. Values obtained by Professor Woodworth in the valley of the Hudson are in close agreement with these figures. In one of his examples such displacements, if present throughout a belt a mile in width, would represent a vertical uplift of no less than 300 feet.

In most of the cases examined, the faults were found to belong not in one but in several parallel series. The more important series, however, of those found along the valley of the Hudson are of such a character as to indicate that a sinking has occurred within a zone which follows

A. A Tank-House in the Santa Cruz Mountains, Overturned during the Earthquake of California on April 18, 1906, with the Foundation not Broken. (After a photograph by Fairbanks.)

B. Post-glacial Faults of Small Displacement near St. John, New Brunswick. (After G. F. Matthew.)

the Hudson River, Lake Champlain, and the Richelieu River from the Atlantic to the St. Lawrence, or a corresponding elevation of the mountain areas upon either side.

Instability of the glaciated region. The country lying between the St. Lawrence River and the Atlantic has been shown to be one of noteworthy instability, even though up to the present most of the recorded earthquakes which have occurred within it have been light. There seems no reason to doubt that the small faultings of the present period which are recorded in the displacements seen on glacially polished ledges have corresponded in time to the earthquakes and to the subterranean rumblings which have been frequent within the region.

Even where the rock surface has furnished no record of such differential movements, because hidden from sight, the local discovery of pebbles which, since their entombment in the bowlder clay, have been broken apart, displaced, and re-cemented, points to the same conclusion. It has now been proposed to establish metal bench marks at favorable points throughout the region, and determine their relative altitudes with such exactness that a repetition of the observations, after a considerable period has elapsed, should furnish data more definitely restricted in time than those which have been above referred to. In some countries where earthquakes are frequent and violent, the repetition of geodetic observations has already conclusively proven that differential changes in level have occurred within very brief time intervals, even though no earthquake faults have been exposed to view.

Within another portion of the glaciated region of North America light is being shed from a different direction upon the problem of bradysismic movement. Since the latest stage of the Ice Age, during which the planing and polish-

ing of the rocks was accomplished, the basins of the present Great Lakes, and a portion of the country which surrounds them, have been successively occupied by bodies of water the forms and areas of which can be quite accurately determined through the study of the now abandoned shore lines. These ancient beach lines have since been tilted upward toward the north and east, as a result of a true bradysismic movement which is even to-day in progress. Upon the northern borders of the ancient basins the elevations of certain of these beaches above the present surface of the lakes is in excess of 500 feet.

Elevated shore lines of the Great Lakes.

The hinge line.

It has recently been discovered through the studies of Leverett that at all points lying to the south and west of a straight line which extends from Ashtabula, Ohio, to Manistee, Mich., the strand lines lie in horizontal planes, or vary from them by such small amounts as to be generally imperceptible. So soon, however, as this line is crossed, the beach lines are inclined in such a manner that they slope toward the south and west, and this slope is much increased toward the northern borders of the basin. This interesting line across the lower peninsula of Michigan has therefore been a fulcrum line about which the northern half of the peninsula has been revolved like a door upon its hinge, and the line may, on this account, be called the *hinge line* (see Fig. 76).

Precise levels which have recently been made to determine the positions of the ancient shore lines on the western side of Lake Michigan point to other abrupt changes in the slopes of the ancient shore lines, and suggest the existence of additional hinge lines lying to the north of the one already determined. A careful study of the seismicity of the region would very likely reveal a relation

between hinge lines and local instability upon the peninsula. Study of a single earthquake, that of September 19, 1884, the only one for which data are available, indicates

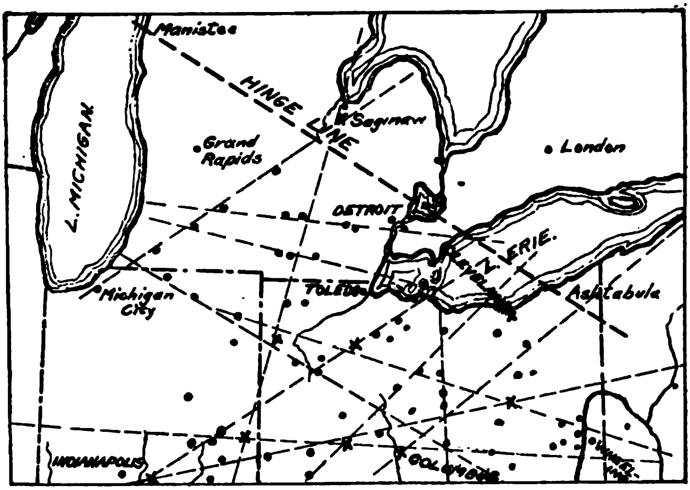

FIG. 76.—Map of a portion of the region surrounding the Great Lakes on which the towns that reported the earthquake of September 19, 1884, have been indicated. The towns which received the heaviest shocks have been entered by crosses. The heavy dashed line extending from Ashtabula to Manistee is the *hinge line* on which the land to the north and east has been tilted in post-glacial time. The finer dashed lines are the indicated seismotectonic lines (data from Rockwood and Leverett).

somewhat clearly that the towns which reported the shocks are ranged upon seismotectonic lines, and that heavier shocks were felt at their intersections.

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CHAPTER XIV

THE STUDY OF EARTHQUAKES UPON THE GROUND

Emergency observations.

AFTER a heavy earthquake the student of seismology is likely to be suddenly called upon to hasten to the stricken district and prepare a report upon the scientific aspects of the disaster. If the disturbance has been a particularly heavy one, he will doubtless find upon his arrival much confusion, and probably, also, great suffering and misery. His duties will require that he leave largely to others the necessary work of succor, and at the earliest possible moment set about the collection of facts which would otherwise soon be past preservation. Other observations, no less interesting and important, are of such a nature that they can be assembled at leisure; hence his first duty is to clearly separate in his plan the emergency studies from all others.

Preparation of photographs the "first aid."

Perhaps the most important of the seismologist's duties will be to preserve a comprehensive series of well-selected photographs. To illustrate what has occurred, if the scale of his investigation permits it, he should go equipped with good cameras, ample supplies of film or plates, and one or more expert photographers. His own time will be fully occupied in selecting the points of view and recording his observations upon them, and he will be greatly handicapped if, in addition,

he is obliged to prepare the more important of his pictures himself. A light kodak may, however, be made very useful for securing views when he does not feel warranted in sparing time for more carefully prepared pictures. Fully half the value of his photographs will be lost if care is not taken to note, with the number of each exposure, not only the exact locality at which it was made, but the direction in which the camera was pointed as well. Equipped with a small hand compass, reading to degrees, it is a comparatively simple matter to note the bearing of the line of vision.

distri-ion and grading he dam- wrought.

Before departing for the earthquake district, it is most important to secure copies of the latest and best maps (and of the city plans for the district) which are anywhere obtainable. Hand in hand with the photographic work must proceed the collection of information upon the distribution of the destruction wrought. Notebook and map in hand, the student traverses the wrecked district, and while memory is still fresh, gathers, sifts, and correlates the observations made by an army of non-scientific observers. If his visit is not made too late, he may personally verify many of the observations reported to him. (For a useful and generally adopted though crude scale of earthquake intensity, see Appendix C.)

points in the

If the funds or the workers at his disposal are sufficient, different parties should begin work independently in different sections of the disturbed district for the purposes of a general reconnaissance. At the end of the first day's work all the parties should, so far as possible, get into communication with each other for the comparison of notes, so that the work of successive days may be wisely planned on the basis of all available

information. Every district will be found to have its key points for study, and it is at such points that the work must be concentrated if the secrets of the earthquake are to be discovered.

The damage to buildings. On account of the varying strength and rigidity of buildings, it is somewhat difficult, upon the basis of damage to them, to gauge the severity of the successional or destructive shocks—a difficulty which is rapidly accelerated with the intensity of the earthquake. In all cases it is important to distinguish the nature of the damage wrought and, so far as possible, to determine how much may be explained by a mass movement of the ground, either upward or downward or laterally, and how much by successional shocks; how far buildings have been split on vertical planes, have been sheared in planes parallel to the surface of the ground, and to what extent bodies have been projected upward from the surface.

When the quaking has not been too heavy, the damage is likely to have been greatest to the chimneys, and the direction which the fallen bricks have taken furnishes one of the most significant and valuable of the available data. After heavier shocks, the distribution and the position of fallen walls is to be carefully noted.

The damage to railway tracks. The scientific student will be greatly aided in his studies of the earthquake, if the shaken district was crossed by railway or trolley lines. No other structures are so generally continuous across the district or so uniform in their strength and rigidity. The obvious necessity that repairs to railway tracks be immediately undertaken renders it essential that provision be at once made for preserving a record of the localities where damage has occurred. Mileposts, culverts, telegraph poles, and uniform rail lengths make this a simple matter, even if it is

left to the scientific worker. If notification is promptly given, however, the desired data can usually be quite as well assembled and supplied by the railroad officials, whose duty it is to report upon and to make repairs to the damaged sections of the track. Experience gathered from the Charleston earthquake of 1886 (see Fig. 77, *A*),

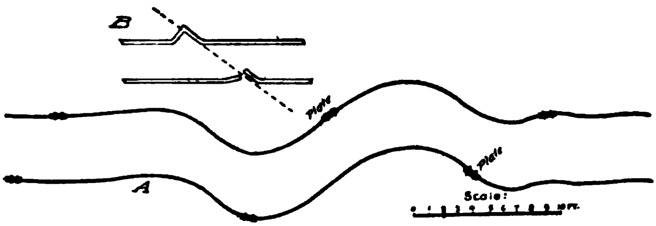

Fig. 77.—(*A*) A kink in railway tracks produced during the Charleston earthquake of August 31, 1886 (after Dutton). (*B*) Damage to track of electric railway south of San Francisco during the earthquake of April 18, 1906 (after a photograph by Moran).

the Quetta earthquake of 1892, the Indian earthquake of 1897, the California earthquake of 1906 (see Fig. 77, *B*), and the Jamaica earthquake of 1907 (see Plate XIV, *A*), is sufficient to show that even in the case of very heavy shocks the damage to tracks is not graded from definite points, but is concentrated within narrow zones separated by relatively wide areas within which the right of way is practically undisturbed.

e evidence r local pansion or ntraction.

The nature of the damage sustained by tracks is differentiated into two classes, in one of which a shortening of the right of way is indicated, and in the other an extension of it. In the first-mentioned case the rails are found to be more or less sharply bent, and, perhaps, kinked; while in the other case the fish plates are torn out and the rail ends separated by intervals

more or less wide. Both these types were illustrated by the railways which crossed the district shaken by the Charleston earthquake of 1886. In addition to the evidences of contraction or expansion of the ground beneath the tracks, other changes are noted, such as elevation or depression of a section of track—which are the result of differential motions in a vertical direction—or horizontal shear along a definite plane intersecting the track (see Fig. 77, *B*).

Damage to metal pipes or underground cables.

Next in importance to the railway tracks in respect to the information they furnish the scientific worker, are the various underground lines of metal, such as water, steam, or gas pipes, and telegraph, telephone, and other cables. Even though not in a strict sense continuous, lines of stone curbing may also furnish quite valuable results indicative of the motions and of

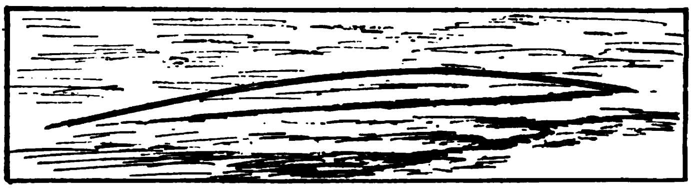

FIG. 78.—A metal pipe buckled and forced out of the ground at the time of the California earthquake of April 18, 1906 (after Dudley).

the changes in volume which have occurred in the local sections of the earth's crust. A compression of the ground reveals itself in a buckling of the pipes, cables, or curbs; and this may be sufficient to bring them above the surface of the ground (see Fig. 78). It has been a rather common observation that the piers of bridges which cross streams have approached each other during an earthquake (see Fig.

79 and Plate XXII, *A*). Where a local expansion of the ground has occurred, it is sometimes found to be recorded

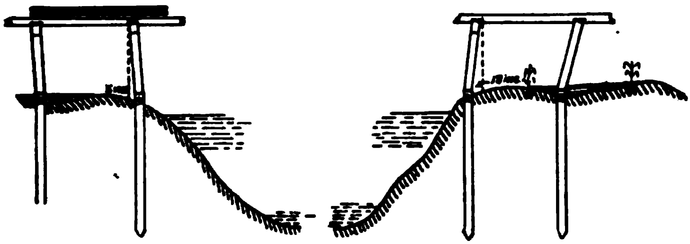

FIG. 79.—Approach of opposite piers of the Ashley River bridge during the Charleston earthquake of 1886 (after Dutton).

in the parting of pipes or cables and the separation of the ruptured ends.

...enings in ...earth ...d differ- ...tial ...anges of ...vel. No observations in connection with earthquakes are of more importance than those which are concerned with the actual measurable adjustments which the surface of the ground has undergone. In the case of very heavy earthquakes these can hardly escape observation if the shaken district is thoroughly explored. In the case of lighter shocks, however, it will be necessary to adopt special devices in order to detect them. In the first case, the faults and fissures at the surface and the arrangement of the craterlets will suggest the outlines of the areas, which may have been independently adjusted and which should, therefore, become the objects of special study.

...ps of ...sures and ...terlets. It hardly needs to be pointed out that all important faults, fissures, craterlets, etc., should, so far as possible, be mapped upon a scale large enough to set forth their size, distribution, and orientation, and measurements should be made not only at the outset,

but at later intervals, of any displacements which are observable upon them (see Fig. 23, p. 71). What will be possible in this direction will depend very largely upon the scale and the accuracy of the available maps for the district. Even in those cases where maps are unsatisfactory it will be possible to prepare a careful map of a small area, well selected to present the characters of the faults or fissures formed during the earthquake.

Study of the underflow of water. An important series of early observations to be made after a great earthquake, concerns the changes in level of the surface of ground water, and the rise or fall of water in fissures. In rural districts a house to house canvass should be made in order to determine what changes have occurred in the level of the water in wells. The date and the time of the day should be carefully recorded for all observations, and these should be repeated later, since it is often observed that the later changes are different in kind as well as in degree from those which immediately follow the heavy shocks. All new springs of water should be located, so far as is possible, and changes in old ones should be carefully noted. The flow of surface streams has at such times often undergone changes which are not explainable by the quantities of meteoric water precipitated.

Early geodetic observations. The first violent shocks of an earthquake are invariably followed by others of gradually fading intensity. While the geological changes produced by the initial shock may never be accurately determined, owing to the fact that no special preparations were carried out in advance, this need not, in all cases, be true of the later and moderately heavy shocks. At the earliest possible moment positions should be selected which command extended views in a number of directions, and definite

PLATE XXII.

A. Nagaragawa Bridge after the Mino-Owari Earthquake in Japan on October 28, 1891. (After Kikuchi.)

B. An Area in the Owens Valley, California, which Before the Earthquake of March 26, 1872, was a Level Plain. (After a photograph by W. D. Johnson.)

lines of sight should be established through the nailing of boards properly adjusted to trees, buildings, or other fixed and fairly rigid bodies. The lines of sight should be reexamined at frequent intervals, and especially after all heavier shocks. To make the method more sensitive, the boards should be planed to an edge upon the upper side, there should be at least three sights in each line (see Fig. 80), and these should not be too near each other.

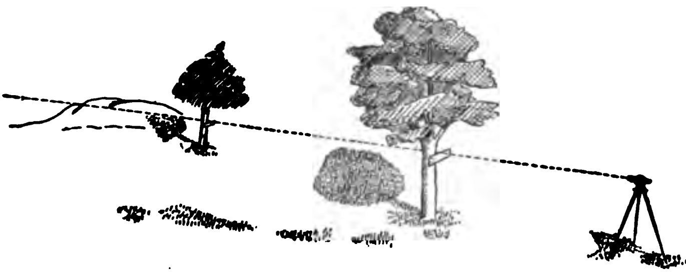

FIG. 80.—Line of sight for determination of changes in level at the time of earthquake shocks.

With the use of a surveyer's transit and stadia, the several lines of sight can be made to radiate from a definite point, at which the instrument is set up, and hence each will be a check upon the other. The telescope of the instrument further permits the use of marks upon each board to determine any variations from horizontal as well as vertical position, while the stadia wires make rapid measurement of the distances between the board signals, and of movements traceable to the shocks, alike possible. In the absence of a transit instrument, simple substitutes may be improvised which will afford valuable, even if less refined, data, provided the shocks have been heavy and the corresponding movements large. Thus, after the great In-

dian earthquake of 1897, marked changes of level were confirmed through a crude application of this principle. The irregular surface of the ground in the Owens valley, California, shown in Plate XXII, *B*, was quite level before the earthquake of 1872 in that region.

Direction of the after shocks.

Much may be learned from a study of the direction of the first heavy after shocks. It is in this case far more important to secure many reliable but not over-refined observations than a smaller number with the use of delicate instruments.

Perhaps the simplest and one of the best seismoscopes, or earthquake detectors, is made by setting up an ordinary lead pencil upon its end in part immersed in a bath of sand. The sensitiveness of this device for detecting shocks may be regulated by the depth to which the end is buried in the sand. Such an instrument is useful not only to register the fact that a shock has occurred in its neighborhood, but it further gives, through the direction of its fall, the initial direction of the shock to a rough approximation. Such a device is so cheap that it can be supplied in any desired quantity, it can be at once reset by unskilled assistants, at the same time that the direction of the last fall is recorded by making a furrow in the sand. Persons can generally be found to examine such instruments at frequent intervals, and a circuit can be made from station to station by one or more persons especially employed for the purpose, who, as they reset each seismoscope, take the bearing of the fallen pencil with a hand compass. Owing to the falling off in the intensity of the shocks, the pencil should be each time immersed a little less deeply in the bath of sand. By simple notches an inch scale may be added to each pencil, and if the depth of immersion in the sand be recorded, a roughly quantitative measure of shock

intensity may be obtained (see Fig. 81). A wooden box, usually available upon the ground, can be used to inclose this simple seismoscope, which should be protected from accidental jars and from meddling persons. It should, further, be in direct connection with the ground.

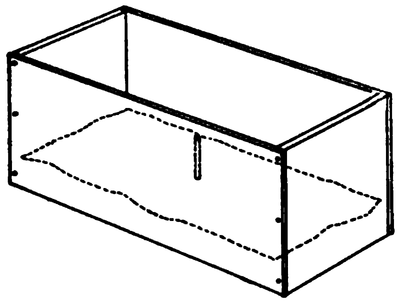

FIG. 81.—Pencil seismoscope to determine the direction of local shocks.

Localities which cannot be quickly reached and personally studied, because of the small force available for the work, can be made to contribute to the study through the use of a system of return postal cards, or some more elaborate method of correspondence. The *questionnaire* is in any case to be recommended because of the promptness with which people can be reached and stimulated to observe the more essential facts; and, further, because with a printed set of questions this work can be largely delegated to unskilled clerical assistants.

The questionnaire.

The list of questions should not be made so long as to impose a considerable burden upon the correspondent. It should, therefore, direct attention to those matters which are of greatest geological interest, such as the faults, fissures, craterlets, new springs, and alterations in old ones, changes of level, etc. If the local teachers, editors, and men of leisure can be enlisted in this work, to distribute the postal cards to intelligent and reliable persons, the investigation will thereby be materially advanced and a waste

of cards avoided. In Appendix E will be found a list of questions which has been prepared for this purpose.

Studies to follow emergency observations.

The later studies of the earthquake will involve the careful correlation and orderly arrangement of the notes gathered, the search in historical documents for records of earlier earthquakes within the district, an examination of the distribution of geological formations, of planes of earlier faulting in them, of the orientation of the network of joints which intersects the rock, and a study of the prominent rectilinear features —the lineaments. A comparison of these different elements will show what relation of position or direction, if any, connects the lines of faults newly opened, or, in their absence, of seismotectonic lines, with the older structural lines of jointing and faulting. Once discovered, lines which possess prominence in any of these respects may be avoided as building sites and utilized for future parks and boulevards.

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EARTHQUAKES UPON THE GROUND

G. K. GILBERT, R. L. HUMPHREY, J. S. SEWELL, and FRANK SOULÉ, San Francisco Earthquake and Fire of April 18, 1906, and their Effects on Structures and Structural Materials. Bulletin 324 United States Geological Survey, September, 1907, pp. 170, Plates 57.

CHAPTER XV

DISTURBANCES ABOVE AND BENEATH THE SEA

The stability of the oceanic areas. EARTHQUAKES, as we have thus far considered them, relate to disturbances upon the continental and insular areas of the globe, where they become manifest in geological changes at the surface of the ground and in displacements of the objects which lie upon it. Our treatment has, therefore, applied to only about one fourth the surface of our planet. What shall be said of the stability of the other three fourths, covered as it is by a fluid envelope to an average depth of more than two miles? It is obvious that we cannot directly inspect the ocean bottom, nor have we to the present devised earthquake apparatus which is suited to delicate observation upon the ocean floor. Even the surface of the sea is seldom explored, save only along a series of narrow zones—the lanes of ocean commerce. On the deep sea and between the continents these tracks of vessels are great circles which connect the more important seaports.

Our only sources of direct observation upon the stability of the ocean floor are the logs of shipmasters and the records of submarine cable companies. This fragmentary knowledge is somewhat extended by observations made upon tide gauges which record the spasmodic and irregular, as well as the astronomic and periodic, disturbances of the

ocean's surface. In a far more important way our knowledge of the changes which take place beneath the sea is being extended through the "distant" observational methods of the new seismology, to be discussed in succeeding chapters.

[Sh]ocks [r]eceived on [sh]ipboard. On vessels at sea, shocks of earthquake produce effects which, when compared, indicate but little variation, save only in their intensity. A rumbling sound is first heard, and this is quickly followed by shocks under which the ship trembles or is so suddenly arrested in its course, that it produces the impression of grounding upon a rock. A number of such shocks may be received in succession, after which the ship appears to slide over the shoal and continue its course as before. When the lead is dropped the ship is perhaps found to be over great depths of water, so that the possibility of grounding is excluded. The fact that the ship has not gone to pieces under the shocks or been left stranded is in itself a criterion of the earthquake. In illustration we may cite the American steamer *Mackinaw*, coal laden from a port in Washington to San Francisco, which at 5.10 on the morning of the recent San Francisco earthquake, and almost over the great earthquake rift where it passes out of Tomales Bay, experienced heavy shocks, as if the ship had struck bottom three distinct times and then slipped over a shoal. The weather was calm and the sea smooth. In the same vicinity and at about the same time the steamer *National City*, in the language of its chief engineer, "seemed to jump clear out of the water, the engines raced fearfully, as though the shaft or wheel had gone, and then a violent trembling fore and aft and sideways, reminding me of running full speed against a wall of ice."

It is a quite general but not universal observation that

the surface of the sea betrays no indication of the seismic disturbance. Though the sea may have been without a ripple and as smooth as a surface of glass, a shock severe enough to startle the crew from deep sleep and bring them rushing to the deck has not ruffled the surface of the water. On March 11, 1855, several ships were lying at separated points within the belt of calms in the South Atlantic, with the water surface as smooth as glass. A seaquake was perceived by more than one of them, though it was not accompanied by the least wrinkling of the water surface. On April 16, 1878, a British fleet was stationed in the Bosphorus when an earthquake was felt on both the European and the Asiatic shores. One of the officers reported that a rare sound was heard, and the ship began to tremble as though it were running upon a sand bank. Persons were overthrown as they hurried up the companionway. The vibration continued some seconds and the water appeared to bubble up beneath the ship, though its upper surface around the vessel remained quiet.

Surface of the sea unruffled.

There are, however, reports of disturbances felt at sea in which the water was raised "as a solid mass" to form a flat dome, but without ruffling its surface, and there are still others in which high but local waves were produced. Unfortunately, we are not in a position to say how many of the disturbances felt at sea might be traced to the eruption of submarine volcanoes. Of many such disturbances the evidences are unmistakable, and the sea is in these cases much disturbed.

Above-sea seismic geography.

The great earthquake catalogue of Perrey, which is the starting-point in all investigations upon the seismic geography of the lands, is likewise a reservoir of data for the oceanic areas. Other reports of shocks

felt at sea, which possess the greatest value, have long been hidden away in nautical magazines, pilot charts, hydrographical and meteorological journals, and the vast number of unpublished logs of vessels. A service of the very greatest value to science was rendered when, in 1887, Professor Rudolph of the University of Strasburg assembled and reviewed a large body of these data in his papers upon " Submarine Earthquakes and Eruptions." Rudolph's

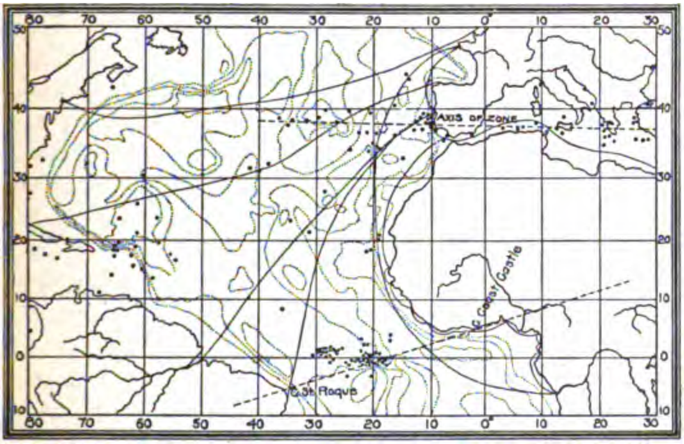

Fig. 82.—Map to show the points where shocks have been felt at sea within the central Atlantic Ocean and the Mediterranean (after Rudolph).

data were from German, English, French, and Dutch sources, so that the American data, affecting especially the near shore regions of the United States, have never been brought together. Moreover, the time is ripe for a reassembling and comprehensive study of all available data, not only along our own littoral, but throughout the oceanic areas. Of all the oceans the Atlantic has been the most

thoroughly surveyed from a seismic standpoint, and thus affords the best basis for generalization. In Fig. 82 is reproduced that portion of Rudolph's map which covers the central Atlantic and the Mediterranean. To it have been added the principal lanes of transatlantic commerce, from which it will appear that the aggregation of observations is not in any important way controlled by the fuller body of observation from these special zones.

The distribution of seaquakes over the oceans.

Upon the basis of his extensive researches upon the seismic geography of the seas, Rudolph has reached the following conclusions:

1. Submarine earthquakes and eruptions occur in all depths of the sea, upon the submarine ridges as well as in the regions of depression.

2. The frequency and intensity of manifestation of the seismic and eruptive forces is not dependent upon the distance from active or extinct volcanoes.

3. There are habitual regions of shock, and portions of the ocean that are quite free from earthquakes; with the exception of the latter, seaquakes occur also isolated and scattered over the ocean.

The study of Rudolph's map (see Fig. 82) discloses the fact that the areas within which seaquakes are common are those of sharp changes in steepness of the ocean floor. Of such areas there are in the Atlantic two of especial note. One of these has a course a little to the north of west, and extends from the eastern shore of the Mediterranean past the mouth of the Tagus, in Portugal, to and beyond the Azores. This almost rectilinear zone extends through 70° of longitude, and has an average breadth of only about 3°. The other zone of high seismicity is directed a little to the north of east along a sharply trenched submarine lineament which joins Cape St. Roque, Brazil, with Cape Coast

Castle on the Guinea coast of Africa, and is very likely continued in the course of the Benue River (see the reference to Hecker's studies on p. 304). The western portion of this zone is continued northwestward to the vicinity of the St. Paul's Rocks.

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nes.

The chief limitation in preparing seismic maps of the continental areas arises from the segregation of the population in villages, and the large tracts of country from which we are, in consequence, without reports upon the local intensity of earthquake shocks. A similar, and in some respects a greater, limitation is imposed upon observations at sea by the restriction of oversea commerce to definite lanes of most direct transit. Since, however, ships move with approximation to a constant velocity, the problem for the sea areas differs in furnishing a series of lines of fairly complete information in place of a series of points much more uniformly distributed.

Professor Rudolph has emphasized the fact that shocks at sea have manifested a selective property in their treatment of ships lying in the same neighborhood. Of vessels less than a degree apart, one has received a shock so heavy as to produce the impression of foundering, while the other has perceived nothing unusual. The earthquake near the Azores, which occurred on December 22, 1884, has, among others, furnished an illustration of this selective property. Later studies indicate, however, that this property is far more precise than Rudolph has supposed. Thus, for example, during the Charleston earthquake of August 31, 1886, of the hundreds of vessels off the Atlantic coast, five only perceived the shocks, and all of the five were located approximately above the strong submerged lineaments of the ocean floor, or over extensions of those clearly marked

out upon the near shores. The ship which received by far the heaviest shock was located over the approximate intersection of strong lineaments (see Fig. 44, p. 114). This ship was the *Nina Mathilde* (Captain Allen), which, when thirty-seven miles northeast of Charleston Light and twelve miles southeast of Cape Romain Light, received so severe a shock that the crew were thrown from bed and thought the vessel was upon a reef. On November 5, 1886, occurred, perhaps, the heaviest of the after shocks of the Charleston earthquake. On this date a captain reported heavy shocks which were felt at sea in lat. 32° 50′ N. and long. 78° 23′ W. This point is at the intersection of the lineaments Σ and 9 of the map of Fig. 44 (p. 114).

Examples from the Lisbon and California earthquakes.

Those ships at sea which reported the great Lisbon earthquake of 1755, were all at the moment either on or near the extension of the lineament of the lower Tagus (see Fig. 56, p. 144). A submarine seismic province of some prominence is located off Cape Mendocino, Cal. If all the recorded seaquakes from this region be plotted, it is soon found that a very considerable number are ranged upon a line which continues one of the faults on which movement occurred during the recent earthquake in California (see Fig. 40, p. 107). Reports of those shocks which were felt at sea upon the Pacific coast on April 18, 1906, and during the succeeding period of after shocks, have now been assembled, and are as follows:

April 18th. Off the Golden Gate near the middle buoy. Steamer *Uarda.*

April 18th. In lat. 38° 23′ N., long. 123° 24′ W. Steamer *Mackinaw.*

April 18th. In lat. 38° 24′ N., long. 123° 57′ W. Steamer *National City.*

August 3d. In lat. 25° 35′ N., long. 110° 6′ W. Ship *Alex. Gibson.*

August 21st. In lat. 26° 19′ N., long. 110° 25′ W. Bark *St. James.*

September 2d. In lat. 43° 40′ N., long. 128° 50′ W. Bark *Agate.*

September 14th. In lat. 41° 18′ N., long. 125° 52′ W. Schooner *Robert Searles.*

November 6th. In lat. 46° 9′ N., long. 125° 22′ W. Schooner *Stanley.*

November 11th. In lat. 42° 51′ N., long. 127° 31′ W. Bark *Carondelet.*

November 26th. In lat. 14° 41′ N., long. 92° 36′ W. Steamer *Newport.*

From the description of these shocks, those which were felt on September 14th and succeeding dates were very much less heavy than the earlier ones. So soon as they are plotted upon a map (see Fig. 83) it appears that with two exceptions all are located either over or near to the supposed course of a zigzagging rift in the vicinity of the Pacific coast of North America. The exceptions are the

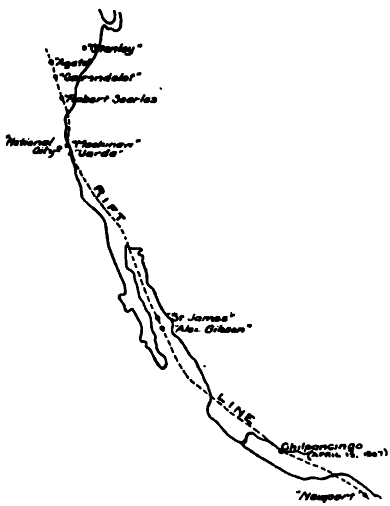

FIG. 83.—Sketch map to show the positions of vessels which felt shocks at sea on April 18, 1906, and during the succeeding period of after shocks.

schooner *Stanley*, which felt a shock off the mouth of the Columbia River, and the steamer *National City*, which was located some distance to the west of the rift line.

The rather rapid dissipation of the energy from movements upon the sea floor which is indicated by the observations, is confirmed by the experiments in connection with the removal by blasting of dangerous reefs, and upon the behavior of sea mines. The most noteworthy result in all cases is the failure to perceive the shocks beyond very moderate distances.

Under-sea changes during earthquakes.

All shocks perceived on shipboard must be assumed to be due to movements which take place upon the floor of the ocean. Our only direct method of investigating such movements is through the deep-sea cables which lie stretched along the ocean bottom. Here, "in the deserts of the deep, or the great gray level plains of ooze where the shell-burred cables creep," the cable is subject to few vicissitudes, and if well made its life may endure for twenty or more years. As soon as the level floors are left, however, and we approach the

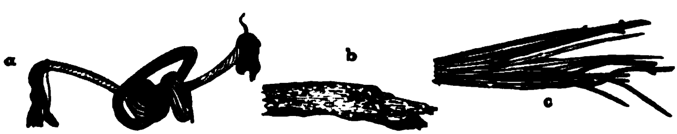

FIG. 84.—Sub-oceanic changes as they are illustrated by fractured submarine cables. (*a*) Compressed and kinked; (*b*) pulled apart; (*c*) broken by tension and the separated wires corroded to needle points (after Milne).

steep walls on the margins of the deeps, the cables are found to be subject to many changes and to interruptions by fracture at rather frequent intervals. They are sometimes bent and twisted; at other times they are crushed or

separated by abrasion; again, they show the effect of tension and are frayed out at the ends; or their suspension in the water is indicated by a coat of shells or coral (see Fig. 84).

According to Professor Milne, who has given much attention to the matter, the explanation which best accords with the observations made in the recovery of fractured cables is that which attributes their dislocation either to a sudden displacement of their bed, or to their burial in material which has slid down some neighboring slope. An examination of some thirty-eight lines, along each of which one or more cables were laid, showed that of 245 interruptions eighty-seven had occurred since delicate instruments have been in use to record distant earthquakes. (Professor Milne's studies were published in 1897, only a few years after the "distant" methods of study had been discovered.) Of the eighty-seven interruptions, fifty-eight, or two thirds the entire number, occurred at or about the time when "unfelt" quakes were registered at European stations.

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Cables have many times been fractured at or near the same point, a point which is generally in the vicinity of a steep slope on the ocean bottom or over some noteworthy irregularity of its floor. Thus the Lipari-Milazzo cable has been five times interrupted near the same point, where it crosses a line marked at intervals by submerged volcanic peaks (see Fig. 85). The latest of these interruptions was during the Calabrian earthquake of September 8, 1905. Nearly all the fractures in the Atlantic cables have occurred near the steep eastern slope of the Flemish Cap, 330 miles from St. John, New Brunswick. Here, at intervals of ten miles, three transatlantic cables run parallel, and on October 4, 1884, all were

simultaneously fractured at points lying in a straight line. Another instance of the alignment of points of fracture has been furnished by the cable laid off the mouth of

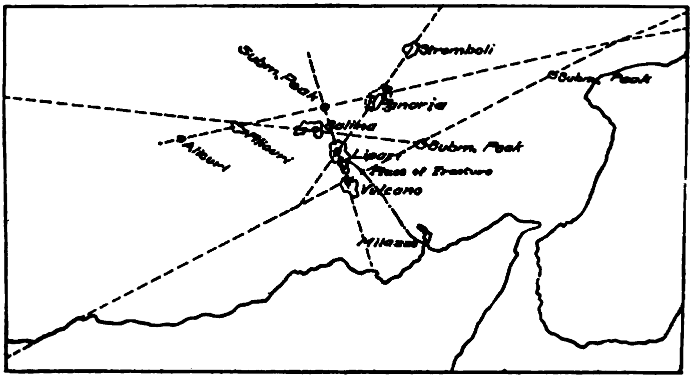

FIG. 85.—Fracture lines indicated by the volcanoes and submerged peaks in and about the Lipari Islands.

the river Rovuma in East Africa (11° S. lat.). In this instance the soundings seemed to show that the sea bottom was nearly level. After the first ruptures, the cable was repeatedly shifted in position in the hope of securing a safer bottom, but the breaks continued, and seven out of the eight recorded were said to be "fairly on the same line."

Movement of sections of the sea bottom.

By far the most instructive series of observations yet made upon changes of the sea floor, through the medium of telegraph cables, is by W. G. Forster, manager of the Eastern Cable Company, at Zante, Greece. The district under his charge was one of great seismic activity and of pronounced irregularities in the sea bottom. Some of the submerged precipices are from 3,000 to 5,000 feet high. Between the bow and stern

soundings of the repair ship differences as great as 2,000 feet have been reported.

At the moment of the earthquake of October 26, 1873, the cable to the mainland broke seven miles out from the Zante office, and was firmly jammed under fallen material in a depth of 2,000 feet of water, where formerly there had been only 1,400 feet. In 1878, in connection with a violent earthquake across the Adriatic, which was lightly felt at Zante, the cable from Zante to Canea (Crete) was broken in two places, 139 and 99 miles respectively from the Cretan end, and so uneven had the ocean floor between these breaks become that it was necessary to make a detour when the repaired cable was relaid. The earthquake of March 28, 1885, again injured this cable at a point where the floor dropped suddenly from 700 to 10,000 feet. In this instance the cable was jammed under a mass of material.

aquakes ar Zante, reece, 1886.

Another of Forster's interesting observations relates to the earthquake of August 15, 1886. In this instance the line from Zante to Crete was in use for a message when the shocks frightened the operator from the office. Only a few moments afterwards, however, the testing apparatus was adjusted, and a dead break in the cable was located twenty-three miles from Zante. On grappling for the broken cable the repair ship made the discovery that to the south of the break the ocean bottom suddenly increased in depth from 4,500 to 5,800 feet. A break occurred in the Zante-Corfu cable during the earthquake of December 7, 1885, where it lay in only 300 feet of water, and only a mile off the Zante shore. With a sea telescope the smooth limestone bottom could be seen, with the line of the former position of the cable marked out upon it; but this line was now two feet away, and the cable

was discovered actually lifted off the bottom. Exactly where the cable had lain at one point there was a deep hole in the limestone, with radiating fractures that suggested the appearance of a large pane of glass which has been fractured. This description recalls the stars of fractures found at Gerocarne after the Calabrian earthquake of 1783 (see Fig. 27, p. 79).

At the time of the great Ligurian earthquake of February 23, 1887, no faults appeared upon the land, but several vessels, a few miles off the coast, received severe shocks. During the following days great numbers of fishes which live only in the deep sea were found dead in the shallow water along the Riviera, or were stranded upon the beach, especially in the neighborhood of Nice.

These data reveal not only the possibilities for further investigation along these lines, but they seem clearly to show that the changes in configuration of the sea bottom take place by leaps and bounds, and in a measure far greater than any which have been observed upon the land.

Submergence of coasts. Some idea of the great adjustments upon the floor of the sea which Forster's soundings and cable observations have made known, we may gain from a consideration of those changes in level which are known to have occurred along the coasts of earthquake countries. In 1692, the former city of Kingston, Jamaica, was submerged, and in January, 1907, another and adjacent section of the coast has been joined to the site of the ancient city beneath the waves (see Plate XIV, *B*). The inner harbor was also sunk during the recent earthquake by no less than twenty-seven feet between step faults along its borders. During the earthquake of San Domingo in 1751, twenty leagues of the coast suddenly sank and has ever since formed a bay. In 1762, sixty square miles of coast in Hindustan

was permanently submerged. Instances of similar, if generally less extensive, submergences might easily be multiplied from the histories of seismically prominent countries.

rthquake ter waves tsunamis. Many earthquakes, and especially those which are chiefly felt along the border of the seas, are often followed by destructive water waves, which, rushing in from the sea, have sometimes caused far greater damage and destruction of life than the shocks themselves. Such after effects of earthquakes were familiar to the Greeks. An instance is furnished by Herodotus, who tells us that in the year 479 B.C., when the Persians under Artabazos were besieging Potidæa, a strong ebb tide set in and continued for a long time. The barbarians, when they perceived the shallows, started to go over to Pallene. When hardly two-fifths of the way across there came a mighty swelling up of the sea such as the inhabitants of the district had never seen. Those of the Persians that were not drowned were destroyed by the Potidæans, who ascribed the overthrow of their enemies to the fact that they had mocked the temple and statue of Poseidon. This interesting episode, probably traceable to a seaquake, strongly suggests the drowning of the Egyptians under Pharaoh Menephtah when he was pursuing the escaping Israelites across the shallow Red Sea, from which region numerous other seismic waves are upon record.

Modern instances of earthquake after waves have been especially common in Japan. In 1854, waves which were 30 feet in height inundated Simoda, and a sea wall was subsequently built to avoid similar disasters. In 1868 waves which originated off the South American coast crossed the Pacific to the coast of Japan, where they rose and fell like a series of tides. In Hakodate, where the ordinary tide is but 2½ feet, the differences in sea level

occurred every ten or fifteen minutes, and sometimes amounted to as much as 10 feet. In June, 1896, such a wave flooded the coast of the Kitakami mountain country in Japan, and cost the lives of 22,000 people. The greatest loss of life from the Lisbon earthquake of the eighteenth century resulted from the tsunami, and not directly from the shocks.

Distribution and registration of tsunamis.

The water wave which followed upon the Lisbon earthquake of November 1, 1755, is said to have been felt almost throughout the civilized world, yet such instances are exceptional, and a compilation of the data by Professor Rudolph shows clearly that tsunamis are chiefly noticed upon the shores of earthquake

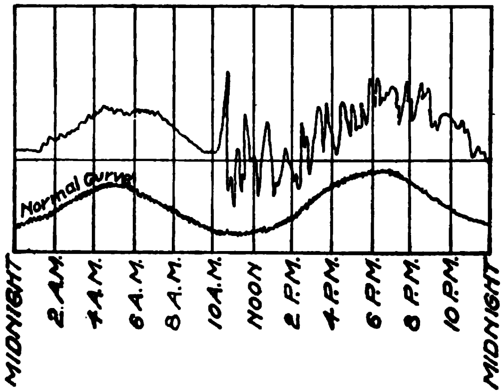

FIG. 86.—Tsunami record superimposed upon the tide curves registered at Negapatam, India, on December 30–31, 1881 (after Rudolph).

countries. Whereas the grander disturbances obviously require no special apparatus for their detection, the smaller ones, especially when observed at distant points, are dependent upon the records of self-registering tide gauges. Whereas the normal curve of the tide record consists of

simple undulations, with the crest and succeeding trough separated by six-hour intervals, the record of the tsunamis is superimposed upon these flowing curves as a series of sharp perturbations, the periods of which may range from a few minutes to a considerable fraction of an hour (see Fig. 86).

[Ini]tial [rec]ession of [wa]ter from [the] shore. It is an observation almost universal, and one of deep significance, that the water wave which sometimes follows an earthquake is preceded by a withdrawal of the water from the shores. That this is not a local phenomenon was shown after the Lisbon earthquake, when the behavior was the same at widely separated points, including Madeira and points in the British Isles. Essentially the same effect has been characteristic of the water waves formed on inland lakes and rivers at the time of heavy earthquakes in the vicinity. In fact, if one will examine the maps of the harbor of Lisbon, he will observe that it is almost a closed inland lake, so that in view of the well-known sinking of the pier and the bottom of the harbor during the earthquake, the Lisbon after wave is much more nearly allied to the waves observed on the Mississippi River in 1811, and upon the Owens Lake in 1872, than with the coincident widespread disturbance of the sea.

[Pro]bable [ca]use of [ts]unamis. Professor Rudolph, whose painstaking and thorough study of seaquakes and tsunamis gives to his opinion great weight, believes the cause of the tsunami to lie in the explosive eruption of a submarine volcano, and to this the phenomena traceable to the great eruption in the volcano of Krakatoa in 1883 has been thought to furnish a parallel. Such an explanation fails, however, to account for the initial recession of the water from the shores. There is, also, a further fact quite incompatible with this theory. The great tsunamis which so often devastate the shores of Japan, in the greater num-

ber of instances proceed from the near-lying deep of the Pacific which is known as the Tuscarora Deep. Those which in like manner inundate the shores of Jamaica, San Domingo, and Cuba, proceed from the Bartlett Deep, which these land masses inclose. The interruptions of telegraph cables at the time of earthquakes have, as we have seen, indicated a deepening of the depressions upon the sea floor, while measurements made upon the shore have quite generally shown that the higher coasts of earthquake provinces are steadily rising. Such depressions of the deeps and uplifts of the neighboring shores probably stand in some sort of balance, and both alike call for an initial recession of the water from all near-lying shores toward the area of depression at that instant when the movement occurs. Such a mass of water as would pile up over the depressed area of the sea floor as a result of the inrush of water from all sides, should be later spread in all directions and roll in to inundate the shores. If this be the true cause of tsunamis, the initial inundation of Lisbon was probably largely local, and the great wave which is said to have raised the surface of the water sixty feet at Cadiz and nearly twenty feet at Madeira, is traceable to the depression of an unknown deep in the Atlantic which is located much nearer to Cadiz than to Madeira. From the heights of tsunamis measured at many points, it should be possible to indicate with some clearness the location of the depressed area, and prompt sounding where the changes are indicated should furnish a definitive answer to the question of origin.

Many earthquakes which affect the seaboard, as, for example, the California earthquake of 1906, are not followed by tsunamis; and we are in such cases led to infer that the movements which occurred upon the continent were

not accompanied by any large movements at the bottom of the near-lying deeps. In the case of the California earthquake, moreover, the movements on shore consisted more largely of adjustments within the horizontal plane. The earthquake in Alaska in 1899 was, on the other hand, characterized especially by vertical adjustments, and it was followed by a water wave which was at least forty feet in height.

locity of propagation tsunamis. It has been found that the progressive movement of such great masses of water across a broad oceanic area, if its time of arrival is measured at a number of points *en route*, affords the possibility of determining the average depth of the ocean along each line of section on which observations have been taken. For this purpose it is, however, important that we know the starting-point of the wave, and as this in those cases which have been measured has been assumed to be some point upon the land, the results which have been secured are likely to need correction.

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CHAPTER XVI

THE DISTANT STUDY OF EARTHQUAKES—SEISMOGRAPHS

seismo-
pe.

It would appear that the earliest instrument for determining the shock direction of an earthquake was made in China by Chi-o-cho in the year 136 B.C. In the interior of a hollow brass globe a pendulum was hidden which was free to move in the cardinal and in the four intermediate directions. Corresponding to these directions eight dragons' heads appeared upon the outer surface of the globe, and within the throat of each was a small ball which could be set rolling by the motion of the pendulum and made to fall into the upturned open mouth of a frog sitting below. If the frog upon the northwest side of the globe caught the displaced ball, the shocks were shown to have come from the southeast.

It is a long interval which separates Chi-o-cho's simple seismoscope and that of the French abbé Haute-Feuille, whose device, invented in 1703, was the first seismoscope to be used in Europe. Since his time seismoscopes have been many and various, but with the advent of self-registering instruments they have almost passed out of use. They may, however, still be made to serve a very useful purpose by reason of their simplicity and small cost, which allow of their wide distribution in an earthquake district.

A typé of seismoscope which has long stood the test of time and is of extremely simple construction, is that of the Italian Cacciatore, known in the Rhine country under the name of the Lepsius quicksilver seismoscope. This instrument is merely a basin filled with mercury to the level of a ring of small holes corresponding in position to the cardinal and intermediate directions, as in Chi-o-cho's device (see Fig. 87). A shock coming from the southwest, for example, causes the mercury to pile up upon the northeast side of the basin, and in consequence spill over through one or more of the holes upon that side. The amounts of mercury which are found in the cups placed beneath each aperture allow the principal shock direction to be determined. An even simpler form of seismoscope and a very practical one has already been described (see p. 235).

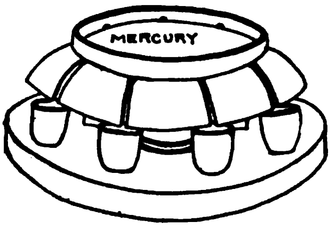


FIG. 87.—The Cacciatore or Lepsius quicksilver seismoscope (after Hoernes).

An absolute seismograph.

If one could only be suspended in space near the earth's surface but without any attachment to it, the problem of registering the earth's motions would be a simple matter. The chief difficulty actually encountered lies in the fact that all bodies upon the earth's surface have the motion of the earth imparted to them. The stars may, indeed, be used as fixed points, and astronomers have often been made aware of an earthquake through the sudden apparent displacement of stars which they were at the moment observing. It has even been proposed upon high authority to construct an "absolute seismograph," by first directing an astronomical telescope at

the polar star and then firmly cementing the entire instrument to the earth by a concrete covering, the field of view of the telescope being naturally made large enough to include the apparent daily path of the polar star in the heavens. It is now only necessary to attach to the telescope a camera which by proper clock work is given a motion in correspondence with the daily motion of the earth, so as to keep the star always in view. Such a seismograph is very sensitive to record a tilting of the ground, but for obvious reasons is not sensitive enough to record vertical movements, and only rarely horizontal movements of the ground.

The universal and unsatisfactory substitute for the theoretical unattached observation station outside the earth is the inertia of rest inherent in a suspended mass —the bob of a pendulum—which as applied in earthquake instruments is termed the "steady mass," "dead mass," or "stationary mass." All pendulums have natural periods of vibration which are dependent on their length, and except in the most improved and elaborate instruments they inevitably combine the motions imparted to them by earth shocks with their inherent natural periods of vibration.

…e vertical …ndulum.

The simplest and earliest form of self-registering seismoscope, or seismograph, is nothing more than a vertical pendulum of ordinary type, which is provided with a marker in the form of a bristle or other flexible extension of the bob, so as to register its motions upon a plate firmly fastened to the earth beneath (see *A*, Fig. 88). When a shock of earthquake displaces the ground toward the right (*B*, Fig. 88) the inertia of the heavy pendulum bob carries it to the left. With the return shock it is apparently moved in the opposite direction (*C*, Fig. 88). The constraint upon the motions imparted to it,

which is imposed by its natural period of vibration, is here so important that the resultant bears no clearly recogniz-

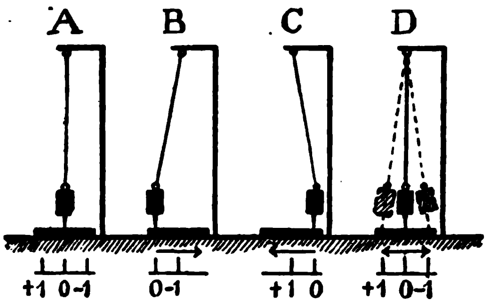


Fig. 88.—An early form of vertical pendulum seismograph (after Sieberg).

able relation to the motions of the ground. A characteristic record is reproduced in Fig. 89.

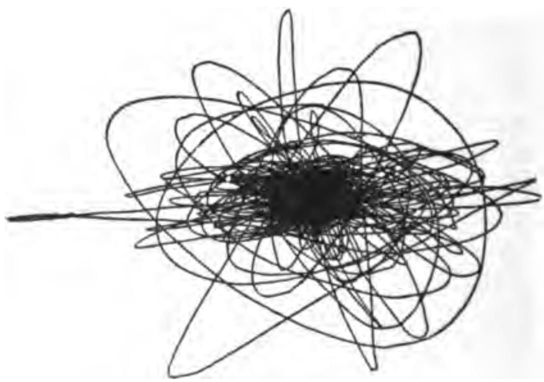


Fig. 89.—The record of an early form of vertical pendulum (after Sieberg).

The simple form of vertical pendulum which has been described, assumes to record the horizontal motions only of the ground. To properly set forth the complex movements

of an earth particle (see Fig. 34, p. 91) we should find it necessary at each instant to analyze the earth motion into three rectangular components, of which one would naturally be the vertical, while the others might well be chosen to correspond to the north-south and to the east-west directions. Most modern instruments are designed to register the horizontal components only of the earth motion. This may be accomplished either by an improved vertical pendulum which has an ingenious mechanical device for separating the two components and recording them as distinct diagrams; or two pendulums may be constructed, each capable of registering one component only of the horizontal motion. Such a single-component pendulum has its plane of vibration nearly horizontal and is known as a horizontal pendulum. Its more essential parts are represented in Fig. 90. The weight or steady mass, G, is firmly connected with the boom, A, which ends in a free steel point, and is pivoted at the other end in an agate cup on the mast or support. The weight of the steady mass is borne by a stay, F, attached near the top of the mast. By lengthening or shortening the stay, the angle, W, which the boom makes with the horizontal, can be changed at will, and the vibration period

hori- tal dulum.

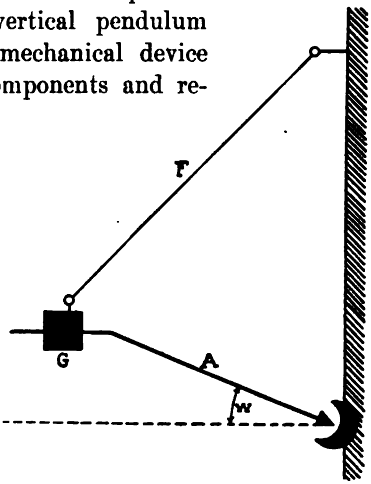


FIG. 90.—Schematic representation of a heavy, horizontal pendulum (after Sieberg).

of the pendulum made long or short in consequence. Such a pendulum is sensitive to all horizontally directed shocks, except such as are in its own plane of rest. An essential part of the instrument which is not represented, is a revolving drum firmly attached to the earth, and so placed as to move the registering paper at a uniform rate beneath and in contact with a marker at the free end of the boom. The friction between the marker and the paper must obviously be made as small as possible if it is not to distort the motion imparted by the earth.

Optical registration. The so-called light horizontal pendulum differs from the heavy one, just described, chiefly in having a lighter steady mass and in replacing boom and stay by a rigid metal frame. In this lighter form of instrument the friction between the marker and the paper

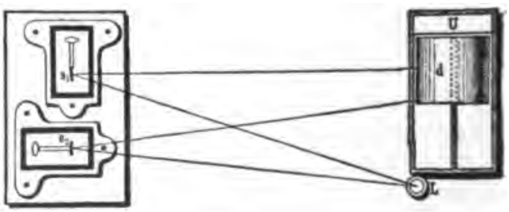


FIG. 91.—Diagram to illustrate the method of optical registration employed in the von Rebeur-Ehlert light horizontal pendulum (after Sieberg).

becomes an even more serious difficulty, and the mechanical registration must of necessity be replaced by a frictionless optical one. The method by which this is accomplished may be illustrated by the von Rebeur-Ehlert pendulum schematically represented in Fig. 91, where the two light horizontal pendulums set up in perpendicular planes are shown incased in closed boxes. The light coming from a slit in the shield of a lamp, *L*, enters through

a slit in each box, and the image is reflected by mirrors fastened to the free ends of the incased pendulums. The reflected images each pass through a slit in the case which covers the registering apparatus and are directed to the photographic paper, *d*, on the surface of the drum, *U*. It is essential to darken the room in which this instrument is used, as the earthquake records first appear when the paper from the registering drum has been developed.

The chief objection to the optical method of registration is the heavy expense of the photographic paper and the consequent contracted nature of the record, as it is usually secured. In most seismographs with optical registration the drum feeds the paper at rates of either four or twelve centimeters per hour, an amount far too small to allow the details of the motion to be distinguished. With the slower rate particularly, the lines of the seismogram are run together and all detail is lost. The von Rebeur-Ehlert pendulum, however, though one of the earliest forms of seismograph, is one of the most sensitive, and has recently (1906) been thoroughly modernized, and its rate of registration increased to ninety centimeters per hour, the standard rate for instruments using mechanical registration. With this improvement it has been possible to reduce the cost of the photographic paper necessary to feed the instrument to about twenty-five cents per day.

90 cms. per hr.

[Me]chanical [re]gistration. In seismographs with mechanical registration the object sought is to reduce friction between marker and paper to a minimum. With the greater number of instruments a smoked paper is used, but in the Italian seismometrographs devised by Agemennone a white paper is used, and ink is supplied from a balanced tubular glass pen. Mechanical starters with electrical connections operate a special device, so that upon arrival of

earth shocks the registering drum is given a double velocity. At the same instant a bell is rung to call the assistant, who sees that everything is in order and that pens are kept supplied with fresh ink. Aluminum rods, glass threads, straws, and other bodies at once light and stiff, are in the various devices for mechanical registration used to greater or less advantage.

Professor Marvin, of the United States Weather Bureau, has greatly improved the methods for mechanical registration by a simple device known as a vibrator. He has found that the point of a stylus, which records the motions upon the smoked paper, tends with the motion of the drum to become so cramped as not to be easily dislodged when the shocks arrive. The vibrator is made from the rewound and slightly modified magnets of an ordinary small electric call bell, and it is attached to the yoke to which the stylus is connected. The current from a small cell keeps the magnets in continuous light agitation manifested by a low hum, and this agitation keeps the point of the stylus half suspended over the paper. Its friction is thereby greatly reduced, and the record so much the more correctly represents the motion of the earth.

Time measurement.

The determination of the instant of the arrival of shocks at an observing station is, particularly in the case of distant earthquakes, a matter of supreme importance. A normal clock, which should keep the correct time with an error of not more than two seconds per week, is employed, and should be compared and corrected weekly by an electric time service wherever this is possible. In isolated stations the time corrections are made through determinations of the sun's altitude by means of a sextant. By a simple electrical device the ticks of the clock are at the end of each minute carried over to the registering

drum, where they impart a kick to the indicator and impose upon the otherwise straight lines of the diagram a series of notches regularly spaced.

ypes and ualities of endulums. The better known modern seismographs fall naturally into two classes according as they are vertical pendulums and single, or horizontal pendulums and double. To the first-mentioned class belong the Vicentini, Agemennone, and Wiechert instruments, and to the latter the von Rebeur-Ehlert, Milne, and Omori types. A third class of seismometer registers, and much less satisfactorily, the vertical component of the earth motion.

Of any pendulum, whatever its construction, the period of vibration may be described in terms of an equivalent simple vertical pendulum of a definite length; and this hypothetical pendulum is generally referred to by the expression, *the equivalent pendulum length.* This length may vary from 1.5 meters (1.66 yards) in the Vicentini short instrument, which corresponds to a vibration period of 1.2 seconds, to 200 meters (about 222 yards), corresponding to a period of twenty-eight seconds in the Omori instrument. The pointer, or indicator, in the registering apparatus of an earthquake pendulum, may be a very complex combination of multiplying levers. It is common to measure its lever property in terms of an equivalent simple indicator, the length of which is described in the expression, *the equivalent indicator length.* The tendency of an indicator to show a measurable deflection in response to earth shocks of any definite intensity may be termed its sensitiveness. This sensitiveness, as a result of the omnipresent friction between indicator and paper, is dependent upon the strength of the earth's shocks. The sensitiveness depends upon the equivalent indicator length, which may vary from a few tens to many thousands of meters. The

magnification of the motion of an earth particle is of importance in fixing the range of usefulness of a pendulum, as it is also in gauging the intensity of the shocks. The magnification varies in different instruments from 7 in the Standard Milne instrument, to 2,200 in the newest and largest of the Wiechert seismographs.

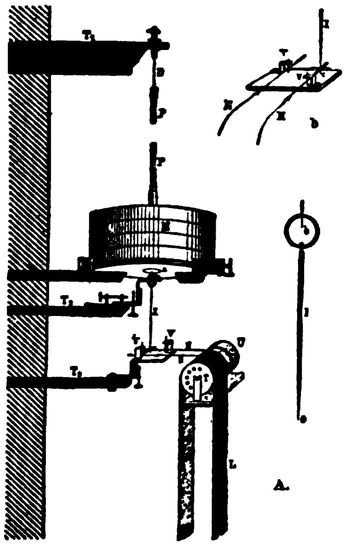
Natural period of a pendulum. A seismograph is most sensitive to those waves which correspond to its own natural period of vibration, as may be simply illustrated by hanging some light object, like a ring, upon a thread and holding the thread between the thumb and forefinger, first at shorter and then at longer distances from the ring. For a particular length of thread the ring takes on a swinging motion from the natural tremors of the hand.

Inasmuch as the period of the earth's vibrations increases the farther they travel, it is evident that an instrument of short period will be better suited to register local and near earthquakes, and one of much longer natural period the shocks which have come from a distance.

Damping. It is this tendency of a pendulum to swing in its own natural period which is the most serious obstacle in the way of accurately registering earth movements. Devices which operate to reduce or neutralize this natural motion of the pendulum and allow the motion of the earth particle to be expressed, are known as damping devices. The principle of their action may be illustrated by the recoil cylinders, which are fitted to heavy guns, by the action of which the recoil movement is in large measure destroyed. All damping devices are alike in this respect, that the earth movement automatically arouses an opposing force, tending to check it by a force which stands in some proportion to the shock which calls it forth. Damping devices make use of the incompressibility of oil

confined in cylinders behind a perforated piston (oil damping), upon the resistance of air to sudden movement of broad surfaces (air damping), or to opposing magnetic attraction so regulated as to increase with the magnitude of the earth disturbance (magnetic dampers). All damping devices alike tend to reduce the amplitude of the motions as recorded in the diagram.

The Vicentini universal microseismograph. This instrument, made in two parts, is constructed to record all the components of the earthquake motion. The apparatus to register the horizontal component represents the type of vertical pendulum, and has a steady mass of 100 kilograms, or about 220 pounds (M in A, Fig. 92), which is suspended from a bracket fastened to the wall, T_1. The motion of the earth is directly communicated to a lever of the second class, l,



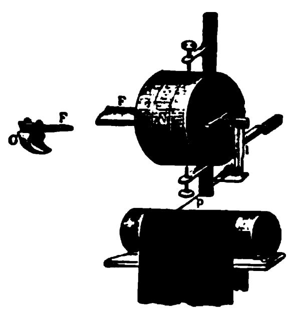


FIG. 92.—Vicentini universal microseismograph. A, Apparatus to register the horizontal components of the motion. B, Apparatus to register the vertical component.

with its fulcrum, *b*, at the lower surface of the steady mass. This motion, magnified by the lever, is divided into rectangular components at the same time that its direction is changed and its amplitude again magnified by a delicate pair of levers ingeniously contrived (see *a*, *b*, *c*, of Fig. 92).

The instrument to register the vertical component of the motion (the form most widely introduced for the purpose) has a steady mass, *N*, weighing 50 kilograms, or about 110 pounds, at the end of a wagon spring, *F*, projecting from a firm fastening upon the wall. The upward and downward motion which is set up in this mass by a shock of earthquake is magnified and changed into a horizontal

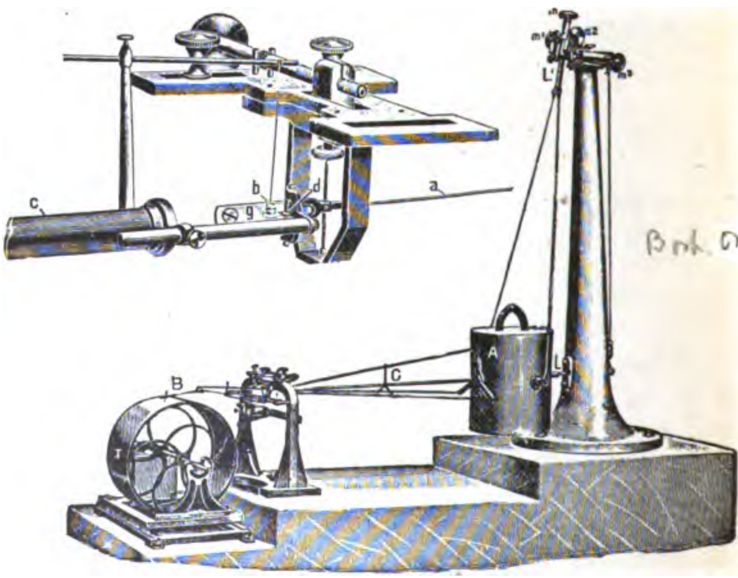


Fig. 93.—Strasburg 100-kilogram pendulum (tromometer). The smaller figure shows on a larger scale a portion of the registering device.

plane by two levers, l and p. All three components of the earth motion may thus be registered, side by side, upon a single roll of smoked paper.

[S]trasburg [ho]rizontal [he]avy [p]endulum—[se]ismometer.

Unlike the Vicentini seismograph, the Omori and the Grablowitz types of instrument are horizontal pendulums, and are always used in pairs. One of these is usually set up so as to register the north-south component of the earth motion, and the other the east-west component. In the Bosch, or European form of the Omori seismograph, sometimes known as the Bosch-Omori, or Strasburg, seismograph, the standard to which the pendulum is attached is a cast-iron column or mast, 1.3 meters (about 1.44 yards) in height. From this mast the steady mass, A (of 100 kilograms—220.5 pounds—in the type figured), is carried by a boom, L, and by adjustable stays supported at the top of the mast, L'. A casting of horseshoe form is firmly bolted to the pier, and carries under its arch in a yoke the device for magnifying and registering the earth motion (see smaller cut of Fig. 93). This instrument has in 1907 been provided with an air-damping device which consists of a broad plate of aluminum hung within a narrow case, and has firmly attached to it a metal rod which projects below the case (see Fig. 94). This

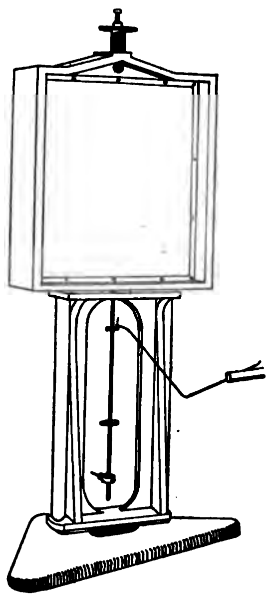


Fig. 94.—Air-damping device attachable to Strasburg heavy, horizontal pendulum.

rod is so connected with the end of the boom of the seismograph that the latter's motions are checked as a result of the resistance of the air which is confined within the case.

The Wiechert astatic pendulum seismometer. A quite different type of seismograph, and here an inverted vertical pendulum, is the Wiechert astatic pendulum seismometer, which is represented in section in Fig. 95. The dead mass, *PM*, is here an iron body weighing 1,100 kilograms, or nearly 2,500 pounds, which is balanced upon a pivot, *D*, and inclosed within a case. A portion of the pendulum in the form of an axle projects above the table, *T*, and the mass is kept approximately in equilibrium through the rod, *Sb*, the balancing rod, *Sta*, and the pair of horizontal springs, *F*, by which it is connected to the table, *T*. From the point, *V*, of the equalizing rod, connection is made with the damping drum, *DT*, upon the one side, and upon the other with the levers H_1 and H_2 of the registering device, by which, with the indicator, *Sf*, the earth motion transmitted through the table is multiplied and changed into a horizontal plane before registration upon the roll of smoked paper, *R*. The instrument is fitted with an exactly similar damping and registering device, lying in the vertical plane at right angles to the section shown.

In this form of instrument the effect of the natural vibration period of the pendulum is completely neutralized by the damping device, and the instrument is said to be astatic. Its success has shown the prime necessity of a general improvement in damping devices, and the makers of other types of pendulum are to-day giving special attention to this feature. Wiechert's seismographs with steady masses of 17,000 kilograms, or nearly nineteen tons, have now been constructed, though upon somewhat different

lines. In such cases the stationary mass is made hollow and is filled with heavy spar, which may be obtained from

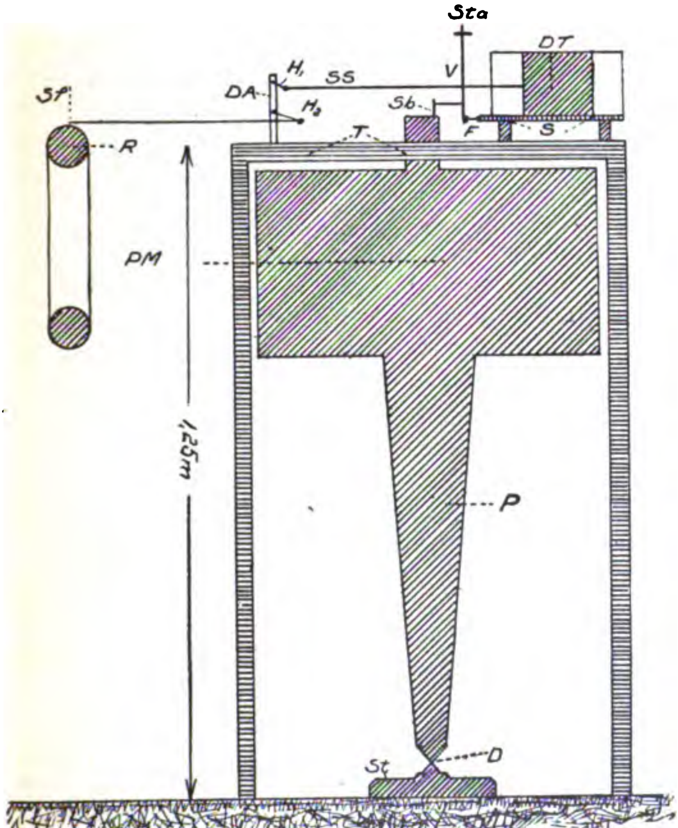


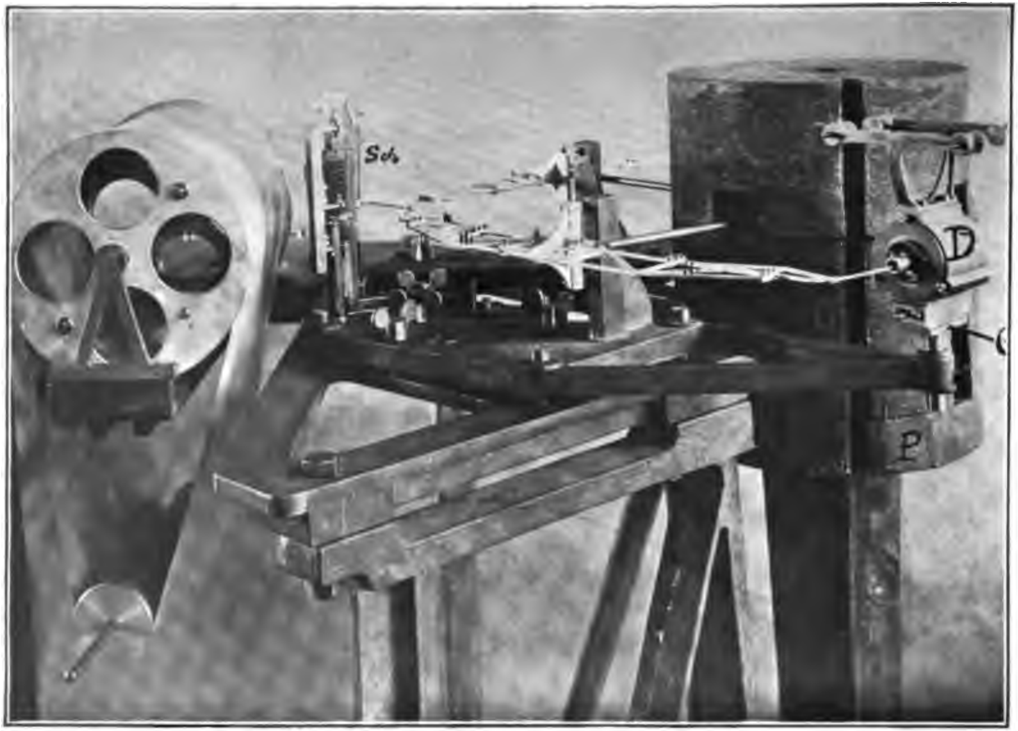
FIG. 95.—Wiechert's astatic pendulum seismometer, shown in a section through one of the damping cylinders (after Sieberg).

any source whatever, after the instrument has reached its destination. With such great weights in the stationary

mass, the friction between indicator and paper becomes a negligible quantity, which, with the astatic feature and with magnifications of 2,200, adapts this instrument to detect extremely small tremors of the earth. Its use is obviously to record the distant rather than the near or local earthquakes. With such sensitiveness and capacity for refined measurement, the larger Wiechert pendulums are difficult to keep in adjustment, and a highly trained physicist and mechanic is an absolute essential to its successful operation.

Wiechert's new small horizontal pendulum.

Except in earthquake stations of the first rank, an instrument is needed which is able to register the more important of the distant earthquakes, and the local shocks as well. Professor Wiechert has, in the summer of 1907, been especially successful in perfecting a pendulum of ingenious but comparatively simple construction in order to meet just such requirements. This instrument, which, without its case, is represented in Plate XXIII, will be understood from the description of the earlier type. The stationary mass, which is here in two parts, G and G_1, is shown at the right of the view mounted upon a common pendulum seat. From the center of gravity of the weights, stiff metal rods communicate the (apparent) motion of the pendulum to trusslike systems of levers, H_1, and these through a rod, *St*, to an axle, *Sch*, on which the writing pens are carried. In the opposite direction the same trusslike lever system operates the air-damping device, D_1—a piston working in a cylinder and sucking in the air through small openings whose size is subject to regulation. The usual weight of the steady mass in this instrument is 80 kilograms, and the rate of registration 36 centimeters per hour, but both these values may be changed and the weight be made as large as 200 kilograms (441 pounds).



THE NEW WIECHERT SMALL HORIZONTAL EARTHQUAKE PENDULUM.

[Ag]emennone [se]ismo-[me]trographs. The Italians have long taken a prominent position in earthquake investigation, and their chief station at Rocca di Papa, near Rome, is fitted up with instruments designed by the distinguished director, Professor Agemennone. These instruments have a sensi-

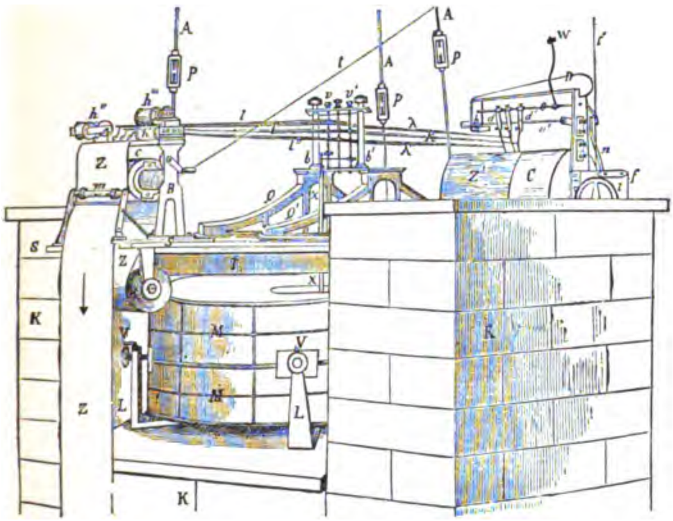


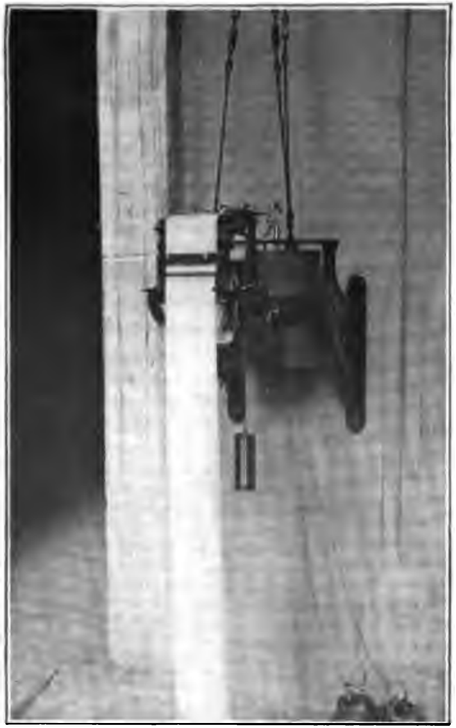
FIG. 96.—Agemennone vertical pendulum with steady mass of 500 kilograms.

tiveness which can be compared only with the elaborate German instruments designed by Wiechert. The more delicate Agemennone seismographs are vertical pendulums, the stationary masses of which have usually the form of a country cheese—they are cylinders of small length but of large diameter (*MM* of Fig. 96). In the axis of the cylindrical steady mass, a well descends to the center of gravity of the mass, and upon the bottom of this well a vertical lever, *X*, is established by means of a pin (not shown in

the figure). An extension of the frame of the instrument, which partakes of all the earth's movements, projects downward into the well and communicates its motion to the lever, *X*, at a point but a short distance above the fulcrum at the bottom of the well. Through this lever of the second class the earth's motion is much magnified, and is again many times multiplied by the elaborate system of levers which are shown at the top of the figure. A peculiarity of certain of the Agemennone instruments is that a device is provided for feeding the registering paper with a double velocity during the arrival of earth shocks (see Plate XXIV, *A*). This result is accomplished through the action of seismoscopes of simple character which, being thrown into vibration, make and close electric contacts. Professor Agemennone has now constructed a so-called microseismometrograph with a steady mass of 2,000 kilograms, or more than two tons weight (see Plate XXIV, *B*).

The seismograph cellar.

The choice of locality is often of importance in establishing an earthquake station. If the instrument to be used is one of long period, as would be the case if it is designed to register especially the heavy distant earthquakes, it may be best set up in contact with the rocky basement, provided, of course, that this is to be found at or near the surface of the ground. For the study of local and near earthquakes, loose soil serves better, because the waves are increased in amplitude in passing through such materials. For a sensitive instrument it is necessary to construct a seismograph cellar beneath the surface of the ground and provided with piers independent of the floor for the mounting of the instruments. It goes without saying that such a cellar should not be constructed near railway tracks, or streets on which heavy teaming is done. The construction of a cellar of the German station



A. Seismometrograph of Professor Agemennone Designed to Double the Velocity of the Registering Drum during Earthquake Shocks.

B. New Microseismometrograph of Professor Agemennone, with Steady Mass of Two and One-fifth Tons, as Installed at the Royal Earthquake Station of Rocca di Papa, near Rome.

for earthquake study at Hamburg is indicated in Fig. 97, and will require no special explanation beyond the statement that the distance of the pendulum pier from the

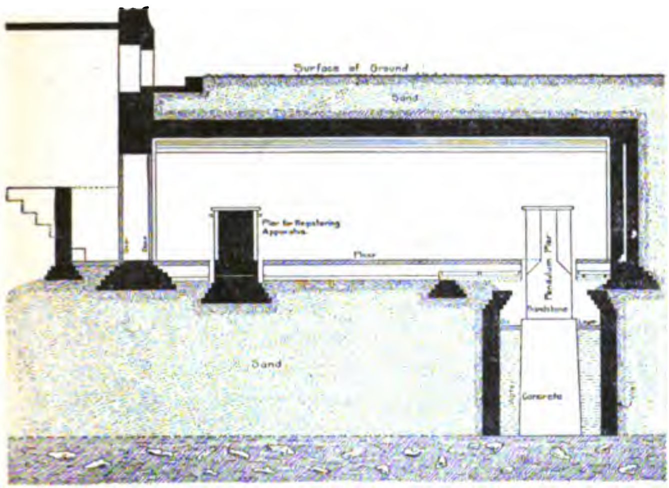


Fig. 97.—Longitudinal section through the pendulum cellar of the earthquake station at Hamburg, Germany (after Sieberg).

pier for the registering apparatus has been here determined by the use of optical registration.

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See also the trade catalogues of seismographs issued by J. and A. Bosch, 15 Münstergasse, Strasburg, the makers of the Bosch-Omori and the von Rebeur-Ehlert seismographs; of Spindler and Hoyer, Göttingen, makers of the Wiechert seismographs; and of Luigi Fascianelli, Via del Caravita 7 A, Rome, makers of the Agemennone seismographs.

CHAPTER XVII

THE INTERPRETATION OF EARTH AUTOGRAPHS

he earth's tograph aracter- tic.

WHEN the early forms of seismoscope gave place to self-recording instruments, or seismographs, the earth may be said to have begun the writing of its autograph, even though the crudeness might suggest that its mark would be a more fitting term. The

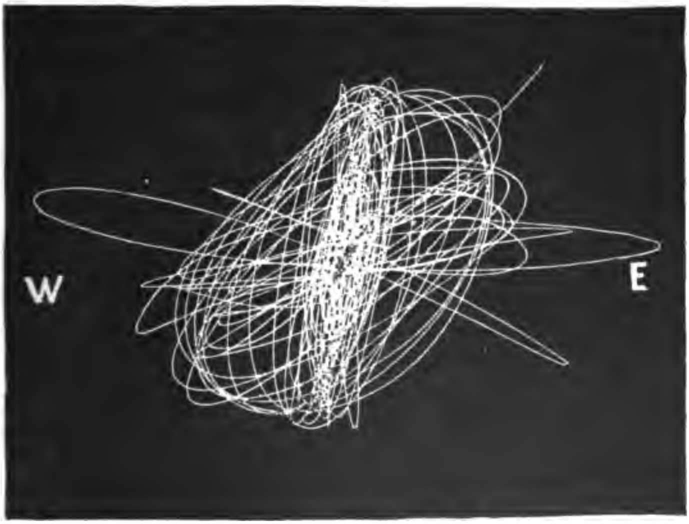


FIG. 98.—The earthquake in the Philippines, April 19, 1907, recorded at the Manila Observatory.

writing of these early seismographs is a scrawl which is more dependent upon the natural period of vibration of the instrument than upon the nature of the motions of the ground (see Fig. 98). If a revolving drum had been used to carry the paper at a uniform rate beneath the marker, the scrawl would, indeed, have been changed into a wavy diagram, but for the reason given this would have possessed little value as a record of earthquake motion. The scrawl assumes to present the motions of the ground in all azimuths of the horizontal plane.

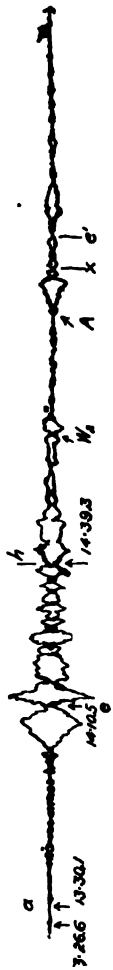


FIG. 99.—Record of the California earthquake of April 18, 1906, written by a Milne horizontal pendulum at Wellington, New Zealand (after Hogben and Omori).

When, in 1894, Professor von Rebeur-Paschwitz was able to show that the motions observed in a delicate horizontal pendulum at Strasburg were due to earthquakes which had occurred in Japan and Venezuela, the modern era of seismometry was inaugurated. To record movements of such small amplitude, instruments of great sensitiveness are required, and it has been a somewhat common impression that a limit is fixed for the refinements of a seismograph by the danger of confusing with earth movements the purely local movements in the air or building surrounding the instrument. It is, therefore, fortunate that the natural autograph of the earth has its distinctive characters which differentiate it from perturbations in the recording instrument due to artificial causes. What these characters are will

more clearly appear as we proceed, but an inspection of Figs. 99 and 100 will suffice to show that such individual and distinctive characters belong to the earth writing.

Modern seismographs, as we have seen, record separately the different components of the earth motion, for which, therefore, either two or three essentially separate instruments are necessary. The vertical component of the motion, which it is the most difficult to accurately register, is

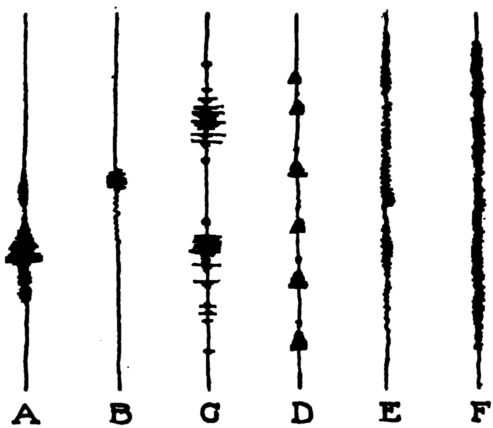


FIG. 100.—Diagrams to show movements registered upon a seismograph by: *A*, earthquake; *B*, persons passing in street; *C*, passing artillery; *D*, cannon shots; *E*, strong wind; *F*, neighboring machine in operation (after Sieberg).

perhaps best obtained by the Vicentini form of instrument, and the rectangular, horizontal components may be studied either by separate instruments, as in the Milne and Omori types of pendulum, or together by a singular instrument, the two components being separated in the mechanical re-

corder of the motion, as is done by the Wiechert and Agemennone instruments.

Optical or mechanical registration.

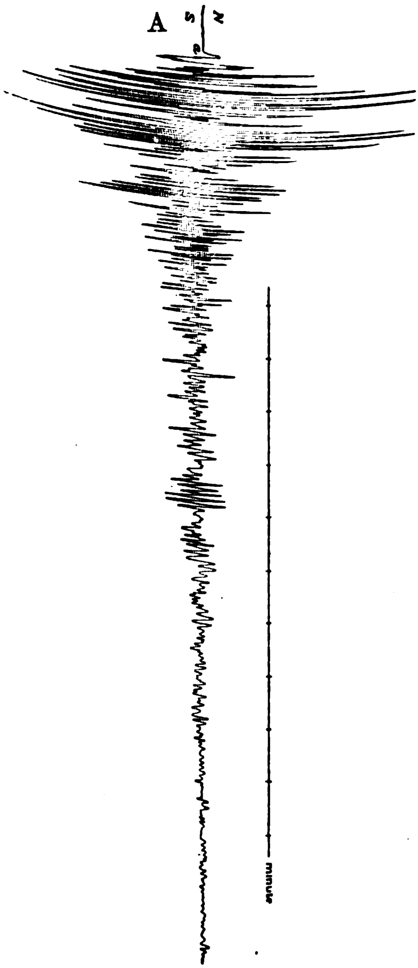
The principal difference between the records from light pendulums with optical registration like Fig. 99, and the heavy pendulums with their mechanical registers, is occasioned by the high cost of photographic paper with which the former must be fed, and the resulting small scale of most of the records which have been secured. Separate vibrations are thus generally run together instead of being separated as they are by the mechanical registering instruments (see Fig. 101, *B*). The light pendulums have, however, the advantage that their records are in no way modified as the result of any friction such as exists between the marker and the paper in the mechanically registering instrument.

Comparison of the records of near and far earthquakes.

A comparison of the seismograms represented in Fig. 101 shows that there is an essential difference between the records of near and of far earthquakes. In the case of near earthquakes the motion imparted to the instrument begins with very nearly, if not quite, its full amplitude, whereas in the case of distant earthquakes the records reveal several distinct types of vibratory motion generally recorded in separate parts of the autograph.

Analysis of distant earthquake records.

There are generally three main divisions and a number of subordinate ones in the record of a distant earthquake as taken by a modern pendulum. The main divisions are known as the *first preliminary tremors*, the *second preliminary tremors* (sometimes lacking), and the *main or large waves*. The first preliminary tremors from the great Indian earthquake of 1897, as registered at the station of Rocca di Papa, near Rome, had an estimated period of 0.5 to 0.8 of a second, and their



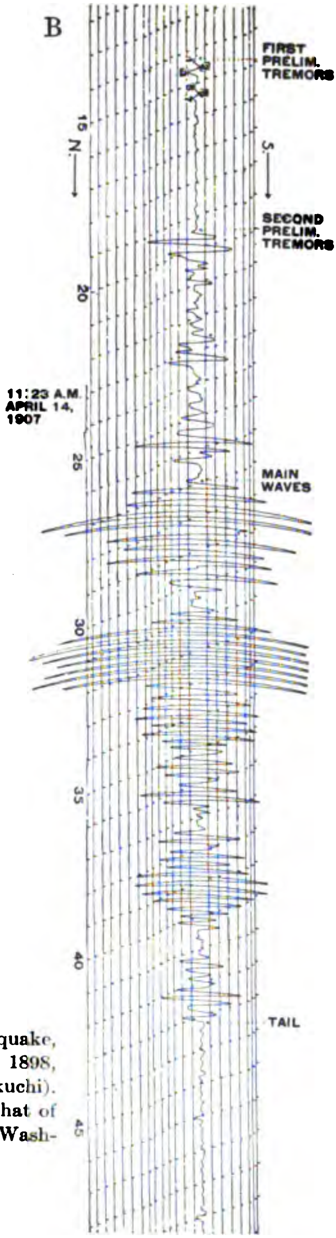
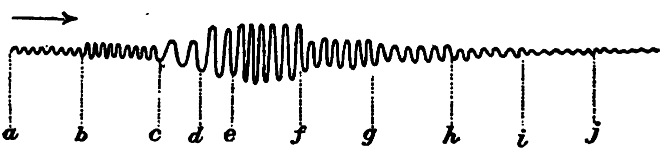


Fig. 101.—*A*, Record of a near earthquake, that of Echigo, Japan, on May 26, 1898, obtained at Hongo, Tokyo (after Kikuchi). *B*, Record of a distant earthquake, that of Mexico, on April 15, 1907, obtained at Washington (after Marvin).

amplitude was but a fraction of a millimeter. The large waves in the case of this earthquake had a complete period of twenty-two seconds, a length of thirty-four miles, and a rise and fall of no less than twenty inches. These waves appear, therefore, to travel like a slow swell along the earth's surface, and they would be felt by individuals save only for the extreme slowness of their motion. It is thus apparent that the main waves show a falling off, in both the rapidity of their motion and in their amplitude, the farther they travel, and an experienced observer can roughly estimate upon this basis the distance of the disturbed area.

Omori's sections of the large waves.

A more elaborate analysis of the records of distant earthquakes shows that the large waves in the seismogram may be further divided into four sections, which are designated by Omori the third, fourth, fifth, sixth, and sometimes additional sections (the first and second preliminary tremors being here included in the numeration). The vibrations of the third section



ab ....1st Section, or 1st Preliminary Tremors.
bc ....2nd Section, or 2nd Preliminary Tremors.
cd ....3rd Section ⎫ ⎧ 1st Phase of the Principal Portion.
de ....4th Section ⎬ Main Part, or ⎨ 2nd " " " " "
ef ....5th Section ⎪ ⎪ 3rd " " " " "
fg ....6th Section ⎭ ⎩ 4th " " " " "
....
j............Tail, or End Portion.

Fig. 102.—Diagram to illustrate the different sections of a "distant" earthquake record (after Omori).

are few and slow, those of the fourth section are somewhat quicker and of very large amplitude, while those of section five are of much shorter period and of large amplitude. The durations of these different sections of the complete earthquake record are roughly equal to one another, if the third and fourth sections be taken together (see Fig. 103). The amplitude is greatest in the fourth and fifth sections. The feeble vibrations which end the seismogram are called its "tail."

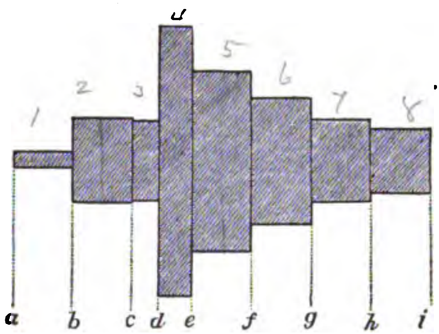


Fig. 103.—Diagram to illustrate the approximately equal length of the several sections in a distant earthquake record (after Omori).

Antipodean resurgences.

The great Indian earthquake of 1897 was the first heavy earthquake upon the land to be studied both by coördinated earthquake stations and by geologists upon the ground. The records of the stations show that the waves traveled not only through but around the globe, thus furnishing a sort of parallel to the atmospheric wave started by the eruption of Krakatoa in 1883. Professor Milne has recently drawn attention to the interesting fact that even in the case of lighter earthquakes from which the energy is so dissipated that no record is obtained at the more distant stations, a distinct thickening of the lines may be noted in those stations which are located at the antipodes. These "antipodean survivors" of the large waves found in the registrations in English earthquake stations can be traced to earthquakes in New

Zealand, and their survival at the antipodes only is to be ascribed to the cumulative effect of waves converging upon the station from many great-circle routes.

Large waves reappear after circuit of globe.

The seismograms registered from some earthquakes of great intensity have revealed more than a single set of large waves, and these have been designated W_1, W_2, and W_3. The first of these to appear in the record have reached the station by the nearest route along the surface (see Fig. 104). The waves W_2

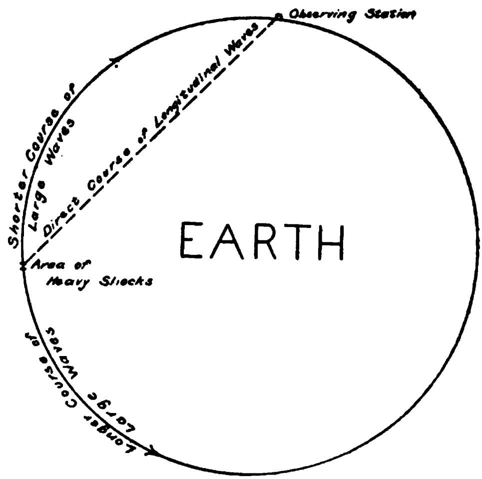


FIG. 104.—Diagram to show the paths of the several waves found in the record of the Chemakha (Turkestan) earthquake of August 22, 1902.

from their diminished amplitude and the time of their arrival, are to be ascribed to vibrations which were transmitted along the surface in the opposite direction over the antipodes; while the waves W_3 are relatively feeble, and the time of their arrival is about three hours and thirty-one minutes behind that of W_1, or that necessary for the

waves of section five to make a complete circuit of the globe with the determined velocity of such waves of about 3.3 kilometers (about 2.05 miles) per second. The seismogram of the Turkestan earthquake of August 22, 1902, reveals these waves W_2 and W_3 with some distinctness (see Fig. 105).

Nature of preliminary tremors and large waves. The waves which first reach the observing station, the first preliminary tremors in the seismogram, appear to have taken a more direct route through the earth's mass. They are, therefore, frequently referred to as the direct waves of the seismogram. It has been rather generally held as a theoretic proposition that these direct waves are longitudinal—that is, com-

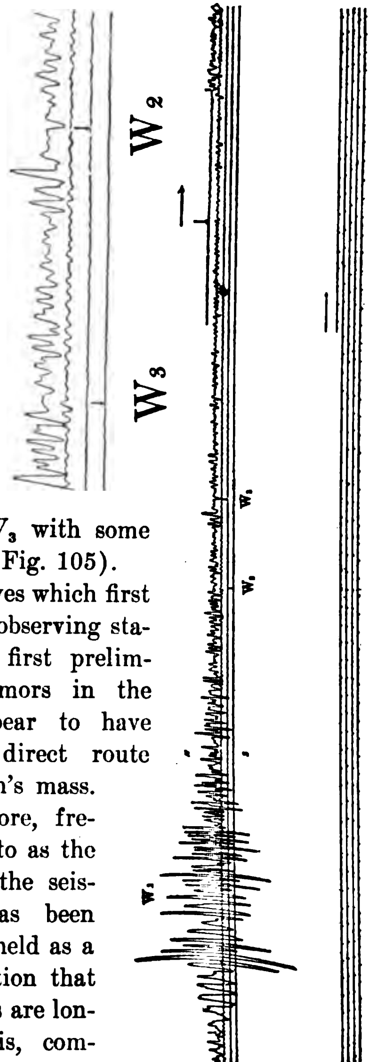


Fig. 105.—Record of the Chemakha (Turkestan) earthquake of August 22, 1902, taken at Tokyo (after Kikuchi). The waves W_1 are the usual surface waves which have come by the shorter route; the waves W_2 are surface waves which have come by the longer route; the waves W_3 are the first large waves, W_1, after they have made a complete circuit of the globe.

pressional—vibrations; whereas the large or main waves have been supposed to vibrate in planes transverse to the line of propagation. A decisive experimental proof of the correctness of this view seems to have been happily furnished by the recent Kingston earthquake of January 14, 1907, registered by the seismograph of the United States Weather Bureau. The two Bosch-Omori pendulums at the Bureau are so placed as to record the north-south and the east-west components of the wave motion. Now it happens that the port of Kingston, which is something more than 1,400 miles distant from Washington, differs in longitude by only fifteen minutes. For our purposes, therefore, Kingston may be considered as located upon the meridian of Washington. Practically *no preliminary tremors were registered in the east-west direction* at the time of the earthquake, though a very distinct series was recorded in the north-south direction. Notwithstanding this difference, the main waves appeared at practically the same instant in the two records, *but the amplitude of the east-west component was about five times that of the north-south component.*

Intensity of shocks measured in the seismogram.

With the constants of earthquake pendulums correctly determined, they afford the possibility of comparing the intensity of shocks which they register. Shocks which in Japan are designated "severe" correspond to a maximum acceleration imparted to the earth particle of a few hundred millimeters per second per second. Shocks just strong enough to be perceptible without the aid of instruments correspond to accelerations of about seventeen millimeters per second per second. By the same measure the maximum acceleration from the great Mino-Owari earthquake of 1891 corresponded to 444 millimeters per second per second.

elocity of the direct waves. The possibility of fixing the location of the disturbed region in the case of one of the so-called "unfelt quakes," inheres in the fact that the waves of heavy earthquakes are transmitted both through the mass of the globe and along its circumference (see Fig. 104). The waves which first reach the station, the preliminary tremors, appear to come by the direct route along a chord through the earth's mass, as is pretty clearly shown by their constancy of velocity when the station is distant and its variability when it is near. For the long distances, the velocity is quite uniform and about 10 kilometers ($6\frac{1}{4}$ miles) per second, so that the diameter of the earth is traversed in about twenty minutes.

The Japanese school of seismologists have generally held that the waves which produce these initial vibrations in the seismogram have an arcual path similar to but deeper than that of the large waves, which follow them in time and are, as all agree, surface waves. The velocity of the preliminary tremors, reckoned on this basis, would be about 14 kilometers (about 8.7 miles) per second, instead of 10. Perhaps the strongest argument against this view is found in the known constants of surface rocks, which do not permit of such a velocity. The apparently uniform velocity of propagation of earthquake waves through the core of the earth is a revelation of the first order of magnitude, for it indicates for the earth a uniformity of composition, and, moreover, a rigidity one and a half times that of the hardest steel.

It seems likely that the value assigned for the velocity of the direct waves may subsequently be somewhat modified, since it has been based largely upon records made upon the light Milne pendulums. Some sacrifice the pioneer must always make, and the standard Milne instrument

suffers in comparison with the later German, Japanese, and Italian types, not only because of its lightness, but because the expense of photographic paper has necessitated a slow movement of the feeding drum and a resulting contracted scale of the seismogram. When compared with the Rebeur instrument, as has now been possible at the Batavia station where a Milne and a Rebeur pendulum have been installed side by side, the records show for the first time that the registration of the shocks begins from one to ten minutes earlier upon the Rebeur pendulum. The preliminary tremors of the Milne instrument may, especially in the case of lighter earthquakes, belong in the second phase of records from more sensitive instruments.

Crudeness of records from Milne standard instruments.

For origins less than 1,000 kilometers (631 miles) distant, the preliminary tremors do not appear separately in the seismogram, and it is supposed that they are combined with the large waves and reach the station with a velocity of about 3.3 kilometers (about 2 miles) per second, with little doubt because of the lower rock densities which are traversed along the shorter and "crustal" chords.

Velocity of the surface waves.

The determination of the velocity of the main or surface waves is subject to some variation because of the recognition of several sections and the necessity of making a choice among them in fixing the velocity. The value given by Milne on the basis of many determinations is about three and a half kilometers per second. The Earthquake Investigation Committee of Japan instituted in 1894 at the suggestion of Professors Sekiya and Omori a system of triangulation which involved the use of four stations provided with exactly similar instruments and so connected by telegraph as to receive uniform ticks from a chronometer. The distances separating the stations varied

from 2.29 to 10.86 kilometers (about 1.5 to 6.8 miles). All instruments being started by the same earthquake, the recognition of special marked vibrations permitted the times of arrival of the same shocks to be compared. The result thus obtained for the velocity of the surface waves of large amplitude (section 5) was 3.3 kilometers per second, or the same as by the usual and natural method.

The correlation with frictional and successional shocks. It is interesting to compare the vibrations registered in the seismogram with the types of shocks which are perceived by the observer upon the ground within the disturbed area. The small amplitude and the rapid period of the preliminary tremors in the seismogram, no less than their great velocity, seem to clearly ally them with the frictional shocks which become perceptible as the premonitory rumblings of the earthquake. As already explained, these direct waves have now been shown by Marvin to be longitudinal, which, taken in connection with their rapid period, fits them to give out a low musical sound. The great intensity of the successional shocks and their vibration perpendicular to the surface of the ground along which they travel, corresponds to the nature of the main waves of the seismogram, as they have been made known through observations upon the recent Kingston earthquake. The well-known lack of any correspondence between the intensity of the sounds and the strength of the shocks which they accompany is in harmony with the view that the former are a consequence of the friction on fracture surfaces.

The second preliminary tremors in the seismogram are not as yet sufficiently explained, but their constancy in the case of distant earthquakes and the law which governs their time of appearance in the record seem to show that they are definite vibrations of a distinct class and not re-

flections of either of the other classes, as has sometimes been supposed.

Calculation of the remoteness of an earthquake.

With fairly uniform rates of propagation established for both the direct and the surface waves originating at any distant origin, the difference in time between the arrival of the preliminary tremors and that of the large waves gives a measure of the distance of the origin from the observing station. For example, a distance of 80° of arc along the surface corresponds to a time interval separating first preliminary tremors and first large waves of about thirty-five minutes. A homely illustration of this method for computing the distance is furnished by a man and a boy starting from the same point at the same instant and traveling with different velocities. It is only necessary to know the exact time when each arrives at a given point to derive the distance of their starting point.

Láska's Rules.

Láska has derived surprisingly simple formulas for fixing the distance of the seat of disturbance in the case of remote earthquakes. If V_1 be the time in minutes of the commencement of the preliminary tremors, V_2 that of the second preliminary tremors, and B that of the main waves in the seismogram; and if Δ be the distance in megameters (1 megameter equals 1,000 kilometers or about 621 miles), then

$$1 + \Delta = V_2 - V_1 \qquad \Delta = V_2 - V_1 - 1$$

and

$$3\,\Delta = B - V_1. \qquad \Delta = \frac{B - V_1}{3}$$

It has been proven by many determinations that these formulas are correct to a close approximation. They may be stated in simple form as follows:

1. *The duration of the first preliminary tremors in min-*

$= 621\,(V_2 - V_1 - 1)$ miles

$(B - V_1)$ miles

utes, less one, is the distance of the seat of the disturbance in megameters.

2. The duration of all preliminary tremors in minutes is thrice the distance of the seat of the disturbance in megameters.

Professor Omori has deduced equations for the distance of great earthquakes differing somewhat in form from those of Láska. For earthquakes less than 1,000 kilometers distant his equation is:

$$x^{km} = 7.27\,y^{sec.} + 38^{km}.$$

For earthquakes which vary in distance from 2,000 to 14,000 kilometers his equation is:

$$x^{km} = 6.54\,y^{sec.} + 720^{km}.$$

Location of distant earthquake from three stations.

It is evident that if the distance of an earthquake from the observing station may be accurately determined, its distance from three or more widely separated stations is sufficient to fix its location upon the earth's surface. From two such stations its location is fixed as at one or the other of the points where the arcs described (upon a globe) from each station with radii equal to the distances as determined from those stations, intersect each other. The arc described by the same method from the third station tells which of these intersections corresponds to the locus of the earthquake. A lack of precision in any of the determinations tends to be corrected as arcs are described from a larger number of stations, and the probability of considerable error may be gauged from the size of the so-called "triangle of error" at the intersections. The simple principle involved in this method will be clear from inspection of Fig. 106.

The deep significance of the modern seismogram having been recognized, the necessity for coördinating the work

of different stations is apparent. Under the leadership of Professor Milne, the British Association for the Advancement of Science has coördinated the work of some forty-five stations well distributed over the surface of the globe, at each of which observations are regularly made upon the Milne standard instrument. Reports from all the stations are forwarded to a central committee of the Association, which, after comparison and study, issues a semiannual report which is mailed to all the stations for further study.

The coördination of earthquake stations.

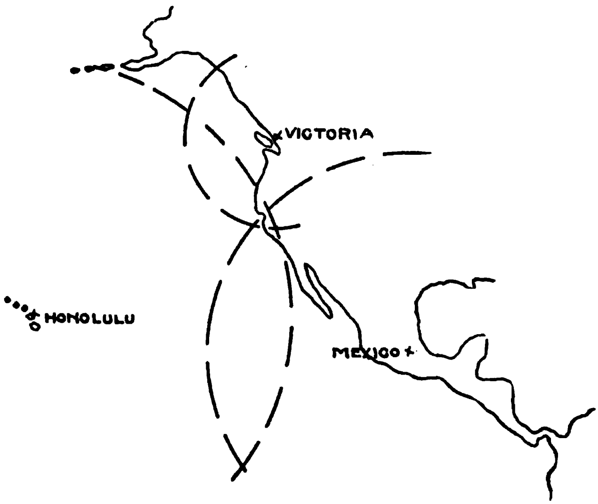


FIG. 106.—Diagram to illustrate the location of a great earthquake from observations made at three widely separated stations.

Japan, with its relatively small but widely extended territory, has at present, in addition to its Central Meteorological Observatory and the Laboratory of the Seismological Institute of the Imperial University (both at Tokyo), 71 local stations provided with seismographs and 1,437

other stations scattered throughout Japan. The 71 stations of the higher class receive standard time by telegraph from the central station at Tokyo.

Coördinated observations in Germany and Italy.

Germany has established no less than twelve earthquake stations of the first rank, in addition to the chief station at Strasburg, where may be found the highest development of instrumental refinement in earthquake study. Here have been held the international conferences upon earthquakes, and here was founded in 1903 the International Association of Seismology.

In Italy the Central Office for Meteorology and Geodynamics, directed by Professor Palazzo, coördinates the work of fifteen seismological stations of the first rank. For collecting information upon Italian earthquakes, there are 150 regular correspondents well distributed through the peninsula and Sicily, and 650 other persons who have agreed to telegraph an immediate report to the central office whenever an earthquake shock has been perceived in their neighborhood.

Largely as a result of the destructive earthquake in Valparaiso in August, 1906, the Republic of Chili has organized a national earthquake service with three stations of the first rank, besides a number of smaller ones, all under the direction of the Count de Montessus de Ballore.

The outlook for the United States.

After Great Britain no nation has better opportunities for establishing a coördinated system of earthquake stations than has the United States. Coming late into the field she will not be required to make the sacrifices of the pioneer on account of earlier and cruder instruments, and her isolated outlying territory is well distributed for the purpose in view. With first-class stations and modern instruments in Washington, New England, the Mississippi valley, California,

Alaska, Panama, Honolulu, Tutuila, Manila, Guam, Cuba, and Porto Rico, much might be accomplished to offset the minor rôle which the nation has thus far played in the recent advance of seismology.

At the meeting of the American Association for the Advancement of Science, held in New York City in December, 1906, a Committee on Seismology, composed of fifteen members, was appointed, and at the initial assembly for organization which was held in Washington, almost upon the first anniversary of the great California earthquake, arrangements were perfected looking toward a differentiation of the seismological work of the different government bureaus interested in science. It has been arranged that the United States Weather Bureau will make application to the next Congress for an appropriation to be used in inaugurating a coördinated series of earthquake stations well distributed throughout the country. Following close upon this movement in the American Association, a number of universities have made provision to set up seismological instruments of modern types.

Earthquake distribution based on distant observations.

It is now hardly a decade since the first coördinated observations were begun at earthquake stations; but the results already obtained from 1899 to 1905 in the location of unfelt earthquakes have been compiled by the veteran English seismologist, Milne. The map of these macroseisms, which is reproduced in Fig. 107, indicates a number of oval areas within which heavy earthquakes have repeatedly been located. These so-called "ovals" are either beneath the sea or along the margin of sea and land, with a much smaller number upon the continents more or less distant from the present shores. Of those located upon the continents and especially upon their borders, the ovals are for the most part well-known

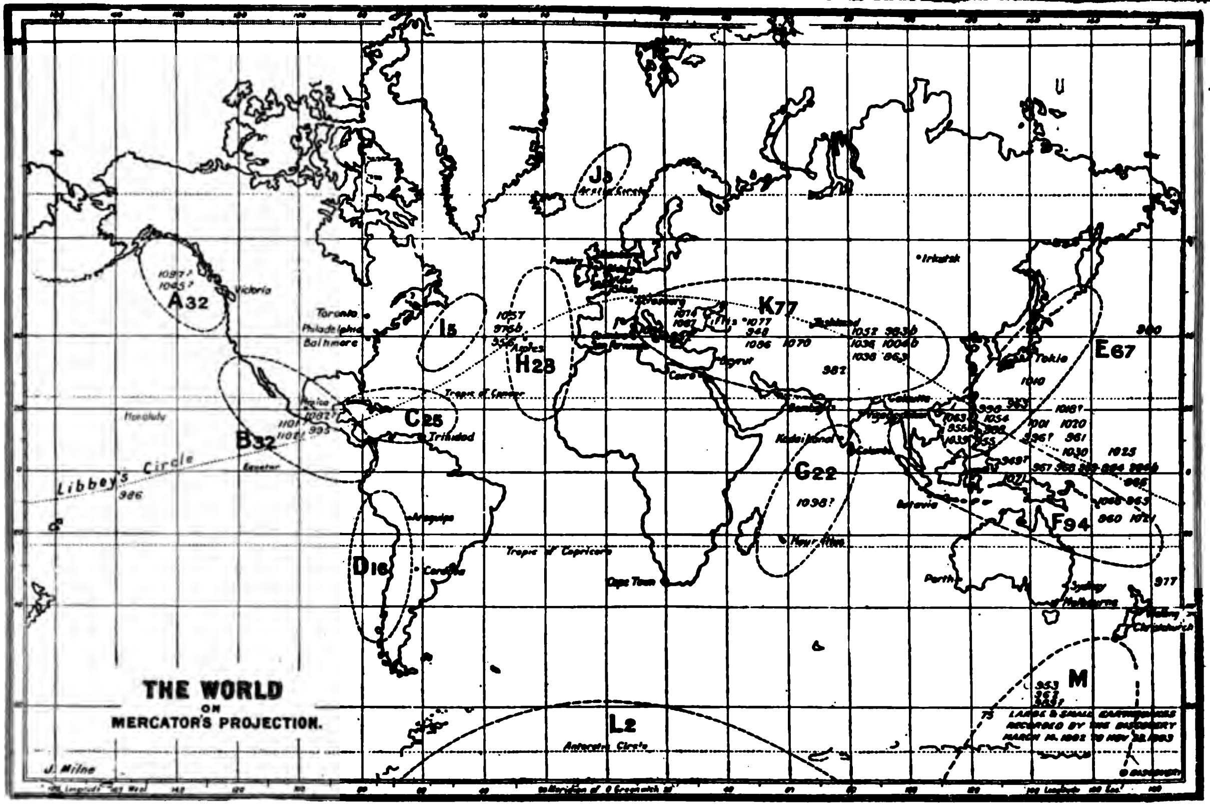


Fig. 107.—Map to show distribution of heavy earthquakes from distant observations between 1899 and 1905 (after Milne).

earthquake regions. The map has been criticised upon the ground that certain well-known seismic regions such as California, Andalusia, Lake Baikal, and New Zealand are not indicated, though Newfoundland and the Indian Ocean are. As regards this objection, it should not be overlooked that regions of high seismicity may not necessarily be regions of equally frequent macroseisms, and the brief period that the method has been in operation removes much of the force of the objection so far as the seismic regions not indicated upon the map are concerned.

As regards Newfoundland the oval merely grazes its corner and is centered over the steep wall of the ocean deep at the margin of the great banks. As this scarp is off the lane of transatlantic steamships, the direct observation of submarine quakes should in any case be seldom made. It is found, however, that on September 27, 1838, the ship *La Claudine* (Captain Blount), while in this vicinity, experienced a most severe series of shocks lasting three quarters of an hour. Nearly all the breaks in the Atlantic cables occur at this wall, and on October 4, 1884, the three cables, running here in parallel lines about ten miles apart, were simultaneously fractured at points opposite each other and in a straight line.

The other oval of macroseismic origins to which objection has been made is likewise seldom crossed by vessels except upon its margin, but we have here the record of severe quakes felt on February 9, 1823, on October 13, 1863, and on January 29, 1882. It seems likely, therefore, that the new method of distant study is greatly extending our knowledge of earthquakes into regions of which we should otherwise have at best but little knowledge, and the confirmation is found for the generalization that much the greater number of earthquakes occur beneath the sea and

along the borders of the great ocean deeps. An earlier map which was published by Professor Milne displayed in addition to the ovals the ridges and the deeps upon the ocean floor, thus bringing out the fact that a definite relationship connects the origins of macroseisms and the pronounced irregularities of the sea bottom. The studies have thus afforded for the oceanic areas a complementary verification of the conclusions of De Montessus concerning the continents, which has been already discussed in Chapter III.

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CHAPTER XVIII

DISTURBANCES OF GRAVITY AND OF EARTH MAGNETISM

The sharp line which separates "near" from "far" earthquakes.

THE analysis of earthquake waves by means of the modern seismograph has shown that a remarkable line of cleavage separates the so-called "near" earthquakes from the so-called "distant" ones. In the diagram of the latter a set of waves of minute amplitude and quick period precedes the arrival of the larger waves by a time interval which is dependent upon the distance of the origin. Inasmuch as these preliminary tremors are continuous up to the large waves of the diagram, they undoubtedly continue also after the arrival of the latter, though they are not generally prominent enough to be identified when superimposed. These preliminary tremors have been shown to be vibrations which have traveled by the most direct route through the core of the earth, of which the density is known to be about $5\frac{1}{2}$ times that of water. The main waves, on the other hand, have traveled by the longer route along the surface of the earth, in which, moreover, density is only about $2\frac{1}{2}$ times that of water. Since waves of any sort have their velocity directly dependent upon the density of the medium which they traverse, the measured velocities of the direct and the surface waves of 10 and $3\frac{1}{2}$ kilometers per second (about 6.2 to 2.2 miles) respectively, are about what we

should expect from the known densities of the materials in which each mainly travels.

The fact of especial significance to which attention should be drawn is, that the approximate distance which separates the "near" earthquake from which the preliminary tremors are absent, from the "far" earthquake in whose diagram they are present, is in the neighborhood of 1,000 kilometers or about 620 miles. The most natural explanation for this rather sharp line of demarcation is that when the "direct" waves travel along the shorter chords of the earth they are largely within the shell of low density and low velocity, and hence more nearly follow the path of the surface waves. Their record should, if this is true, be superimposed upon that of the main waves and hence lost.

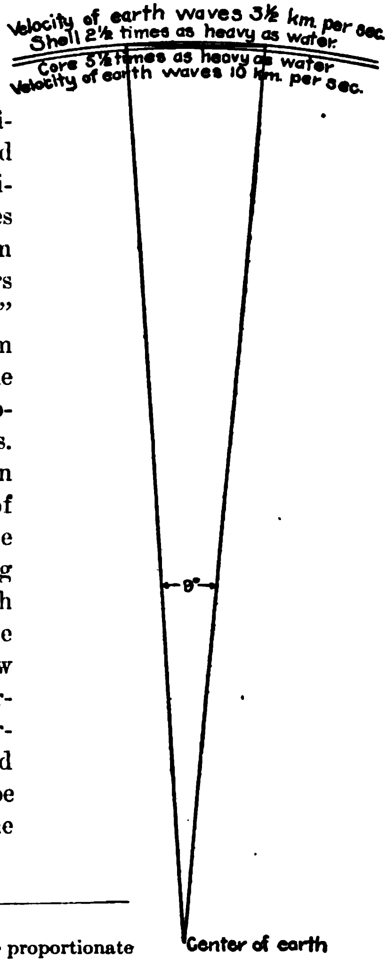

FIG. 108.—Diagram to illustrate the proportionate thicknesses of the core and of the enveloping shell of the earth, based upon the observed velocities of earthquake waves.

Measure of the thickness of the earth's "crust."

The chord of 1,000 kilometers measured upon an arc of the earth's surface subtends an angle of about 9°, and its deepest point is only about twelve and a half miles below the surface. The conclusion to be drawn from this consideration is that the shell of the earth meets the core of denser material on an unexpectedly sharp contact surface, which is less than twelve and a half miles below the outer surface of the globe, and probably little more than half that distance (see Fig. 108). The shell, or crust, would thus be proportionately thinner than the shell of a hen's egg. We shall see that there are some irregularities in the value of gravity and in the terrestrial magnetism which find an explanation upon this hypothesis.

Geographic distribution of abnormal values of gravity.

The pull of the earth exerted upon bodies above its surface is such that when they are free to fall they acquire a velocity in a second sufficient to carry them a little over 32 feet during the next second. This value, which is known as the acceleration of gravity, and is written, g, is smaller as we get farther from the earth's center, and hence must be measured at sea level or corrected in accordance with a determined law. Owing, further, to the earth's spheroidal shape, gravity varies also with the latitude of the place at which it is measured. The local value of acceleration is not usually measured in connection with a body falling freely, since it can be as correctly and more conveniently determined from bodies constrained in their motion, as is, for example, an ordinary pendulum. The period of a pendulum's vibration is quicker the greater the force of gravity, so that it swings more rapidly at points nearer the center of the earth. Observations to determine the local value of gravity, known as pendulum observations, have now been

made at many points which are scattered over the continents, and these reveal variations which are not explainable either by the altitude or the latitude at the place where the observations are made.

Many of the abnormal values of gravity are clearly due to the proximity of mountain masses, which, as they exert their pull upon the pendulum bob, materially alter its period of vibration. The point A, in Fig. 109, should be

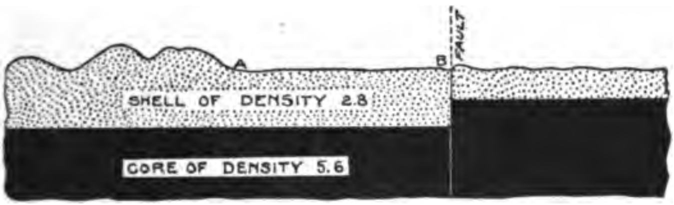

Fig. 109.—Diagram to illustrate some causes of the abnormal values in the local acceleration of gravity. *A*, A point upon the surface where gravity is strongly influenced by neighboring mountains. *B*, A point where gravity is affected by the elevation along a fault of a portion of the dense core of the earth.

one of abnormal value of g, due to the neighboring mountain mass, and it is thus possible to "weigh" the mass of the mountain with a pendulum.

Relation of the zones of abnormal gravity to earthquakes.

Just as a heavy mass above the general surface of the earth exerts its pull upon a pendulum, so any mass of unusual density located beneath the surface should exert its effect. The chief difference is that the one mass is exposed and its bulk and probable density are a subject for computation, while the bulk and density of the other must be based upon inference only. If it be true that the low densities known to be characteristic of the rocks within the earth's crust are restricted to a thin shell, as is inferred from the velocities of earth

waves, then it follows that a considerable vertical displacement of portions of the shell along faults should be detected by abnormal variations in the local values of

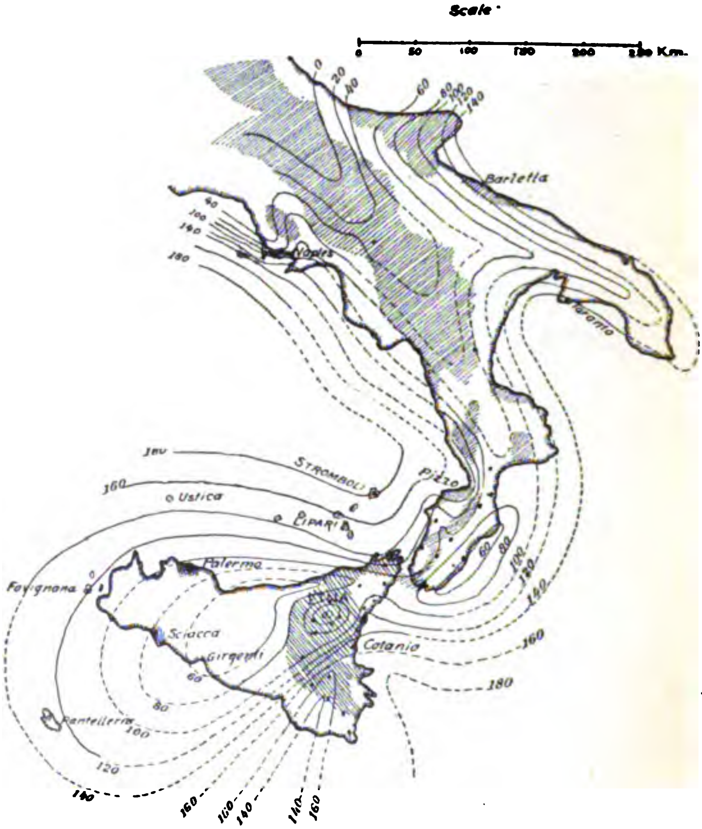

FIG. 110.—Map of southern Italy and Sicily to show the distribution of variations in the value of gravity. The curving lines connect those points upon the surface which are characterized by the same amounts of variation from normal values (after Riccò).

gravity, values which are not accounted for by the peculiar topography of the country (see B in Fig. 109).

It has recently been discovered that in certain provinces, at least, a correspondence exists between zones of faults upon the surface and earthquake belts on the one hand, and zones of abnormal gravity upon the other. As yet, comparatively few studies of this nature have been made, but in Russia, in India, and in Italy, independent investigations have led to the same conclusion. Previous to the heavy earthquake of Calabria on September 8, 1905, a royal commission, headed by Professor Riccò, had completed a study of the distribution of the acceleration of gravity over southern Italy and Sicily. The results show that the most marked changes in this value (where the so-called isoabnormal lines are most crowded, see Fig. 110) are at the borders of the great Tyrranean deep of the Mediterranean, lying between the peninsula of Italy, Sicily, and Sardinia; and that these zones correspond to the areas of important faults and to great instability—they are the prominent earthquake belts of the region. A new royal commission, headed by Professor Riccò, is now to repeat the earlier work, and thus determine whether changes in gravity may be traced to the movements which brought about the earthquake in September, 1905. There are few more promising fields of inquiry into the nature and structure of the interior of the earth than this of the distribution of the value of gravity.

stribution gravity er the eans. The earliest modern determinations of gravity within the oceanic areas were made upon islands situated far from the mainland of Asia. The results obtained were so abnormal as to allow the conclusion that gravity is generally above the normal value over the seas and below it upon the continents. Thus, it

became common to speak of continental and insular values of gravity. Until quite recently there has been no method of measuring the value of gravity over the open sea, and Professor Rudolph, writing in 1887, said: "Pendulum observations upon the sea must hence be regarded as a pressing need of scientific investigation if we are to come to a better understanding of the structure of the earth's crust and the operation of the geodynamic forces." With the discovery of a new and simple method for measuring gravity, and one suited to use upon shipboard, observations were made in 1902 on a voyage between Hamburg in Germany, and Rio Janeiro in Brazil. The results of these studies were a great surprise, because they showed that with comparatively small variations gravity was the same over the sea as at sea level, and in the same latitude upon the land. It is, however, significant that the places where variations in gravity were chiefly observed lie over the steep slopes of the ocean floor along the line traversed. These points are: (1) At the sudden passage from the Gettysburg Bank to the great deep near the Canary Islands; (2) at the rapid descent of the sea floor between St. Paul's Island and the equator; and (3) at the rapid rise near Cape St. Roque, Brazil. From Hamburg until over the descent at the north of the Bay of Biscay, the variations of the acceleration of gravity did not exceed 15 units, whereas they here increased to 177 units. Remaining near zero, along the coast of Portugal, they suddenly increased to 152 units off the mouth of the Tagus, and near a descent to depths of 5,000 meters (about 16,400 feet).

The measurements made at Bonin upon the basis of which the idea that gravity is uniformly in excess over the seas was reached, are in the light of these observations

otherwise accounted for, for Bonin is a sharp ridge from which the sea bottom descends steeply upon both sides to depths of over 6,000 meters (about 19,680 feet). The excess of gravity over normal at Bonin was found to be no less than 257 units, though in the Atlantic over flat sea floors 4,000 to 4,500 meters (13,120 to 14,760 feet) below the surface the value is normal. As has been found to be the case upon the land, the points of maximum abnormal gravity are upon the sea the zones of extreme instability—the belts where seaquakes have been most frequently felt in the Atlantic (see Fig. 82, p. 241). These areas of steep slope, of maximum abnormality of gravity, and of maximum of seismicity may, therefore, be safely designated as zones of dislocation or faulting.

gnetic sturbances ring rthquakes. It has long been known that magnetic needles have been often disturbed during the passage of earthquake shocks. Shortly before the earthquakes at Lisbon in 1755 in many physical laboratories scattered throughout Europe, the armatures suddenly dropped from horseshoe magnets. Alexander von Humboldt, who experienced many earthquakes, tells us that during the earthquake of Cumana, on November 4, 1797, the magnetic inclination at that place was reduced by ninety centesimal minutes, though in other heavy earthquakes no change occurred. It is this lack of uniformity of the observations, which has been characteristic, that has caused the magnetic perturbations described as occurring during earthquakes, to be either doubted or to be ascribed to mechanical causes only. Automatically registering magnetic needles, or magnetographs, which are now installed at many stations scattered over the globe, have added much to our knowledge of this subject, while confirming the variation in the results which was before observed.

After the Laibach (Austrian) earthquake of Easter, 1895, the magnetographs located in Milan, Italy, Pavlovsk, Russia, Potsdam, Germany, and Vienna, all showed marked perturbations. The magnetogram registered at this time in the Vienna observatory showed a sudden interruption and wide displacement (see Fig. 111). In 1887 a magnetic survey of Japan was carried out, and in October, 1891, occurred the great Mino-Owari earthquake. During December and January following the earthquake a magnetic resurvey was made within the region chiefly affected by the shocks in order to determine what changes, if any, had occurred in the magnetic constants of the province. To quote the language of Baron Kikuchi, it was thus learned that "there had been a most remarkable change in the isomagnetics of the district.

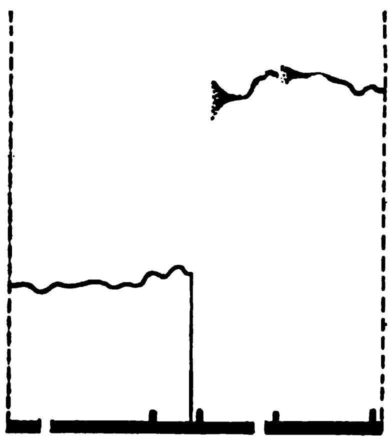

FIG. 111.—Disturbance in the terrestrial magnetism at Vienna during the Laibach earthquake of Easter, 1895 (after Liznar).

The magnetic disturbances are local.

With the object of learning how the magnetic perturbations are related to the shocks from great and distant, or world-shaking earthquakes, Professor Milne, in 1897, prepared a list of the dates of larger earth movements of which the centers of disturbance are known. This list was forwarded to thirty-two different magnetic observatories, with the request that

comparison be made with the magnetograms which were on file at each place. From the replies returned, it appeared that whereas at some stations the magnetic needles are seldom, and then only slightly, disturbed at the time of great earthquakes, at others they so frequently respond to the earth shocks that their records have a seismological value. The case of Toronto in Canada is especially interesting. The magnetographs in Toronto itself did not respond to earthquakes, whereas after the station had been removed to Agincourt but a few miles away, responses had been frequently noted. When, now, the values of gravity at each of the stations included in the *questionnaire* are considered, it is found that the magnetographs respond to earthquakes *at those stations only where gravity is most abnormal.*

A movement of a portion of the dense magnetic core of the earth upon a fault (as at *B*, Fig. 109) should induce perturbations in magnetic needles in the vicinity. Now the mere presence of large magnetic masses in the neighborhood of a compass, or under certain conditions at considerable distances, causes its directive property to be to a large extent neutralized, so that it becomes sensitive to very slight jars. In the above described conditions we may see a possible explanation of ship's compasses suddenly and temporarily becoming "crazy" and failing to indicate the pole. On April 17, 1907, while between lat. 42° 20′ and 42° 40′ N., and long. 53° and 55° W., the steamship *La Provence* was unable for a considerable period to steer upon its course owing to the fact that the ship's compass completely lost its directive quality. Milne has been inclined to believe that where magnetographs respond to earthquakes with special readiness "a hidden chain or mass of unusually dense material" underlies the vicinity of the

station. "In other words, the value of g at these stations should be greater than at those stations where magnetic needles are not disturbed." Observations made in Japan in those instances where magnetic disturbances seem to have been of very limited extent permit of a calculation of the distance above or below the earth's surface where the source of the disturbance is located. These calculations show that the height or depth of the source is small compared with the distances which separate the observing stations.

A threefold correspondence. To his interesting studies upon the distribution of gravity Professor Riccò has since added an examination of the distribution of earth magnetism (see Fig. 112), and the results may be summed up in his own words: "We may, therefore, conclude that in eastern Sicily, also, we have the threefold correspondence of singular instability, or seismic activity, with noteworthy anomaly of gravity, and with irregularity of terrestrial magnetism."

The scattered observations which have here been brought together are but beginnings, though significant ones, and it seems likely that the near future will bring many studies of a related character.

Possibility of predicting earthquakes. When in accordance with an Imperial Ordinance, dated June 25, 1892, the famous Earthquake Investigation Committee of Japan was organized; its objects were stated to be: "In the first place to investigate whether there are any means of predicting earthquakes; and in the second place to investigate what can be done to reduce the disastrous effects of earthquake shocks to a minimum, by the choice of proper structures, materials, position, etc." The committee has included some of the most brilliant scientific men of Japan, and has now worked

enthusiastically and tirelessly for a period of fifteen years; but it is necessary to admit that the last-named endeavor is the only one which has been crowned with success.

This much, however, may be said, that when earthquakes are light and frequent, danger is much less than it is during a complete cessation of shocks. The philosophy of this seems to be that if adjustments in level within the crust are frequently made they are so much the less severe, whereas stresses may gather during a temporary cessation of earthquakes until they are finally able to overcome a greater resistance with proportionately greater violence. There is, however, one hopeful outlook for the future. Magnetic disturbances in Japan, particularly, have generally preceded earthquakes by a period measured in days more often than hours, and the Japanese are hopeful that in this circumstance lies

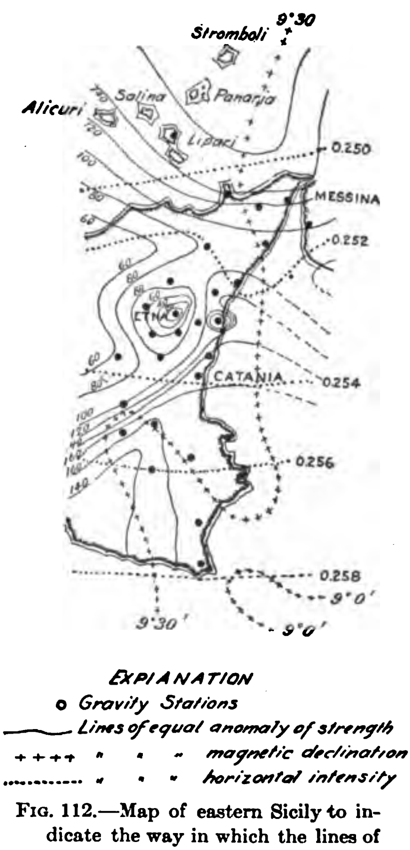

FIG. 112.—Map of eastern Sicily to indicate the way in which the lines of equal earth magnetism (horizontal component of intensity) are crowded together or deflected in crossing earthquake districts (after Riccò).

the possibility of giving warning of earthquakes by a time interval sufficient at least to greatly reduce the loss of life.

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1880. Transactions of the Seismological Society of Japan. Vols. I–XVI (1880–92). Continued as the Seismological Journal of Japan. Vols. I–IV (1893–95), Edited by Prof. John Milne.

1887. Gerland's Beiträge zur Geophysik. Vols. I–VIII; Supplementary Vols. I–III (1887–1907). This is the organ of the International Seismological Association, and is edited by Prof. George Gerland, Director of the German Chief Station for Earthquake Study at Strasburg. Printed by Wilhelm Engelmann of Leipsic. The papers are printed in any one of the four languages, German, French, English, or Italian.

1895. Bolletino della Società Sismologia Italiana. Edited by Prof. Luigi Palazzo, Director of the Central Office for Meteorology and Geodynamics at Rome. Published since 1895.

1896. Reports of the Committee on Seismological Investigations. Printed in Reports of the British Association for the Advancement of Science. Edited by Prof. John Milne, Secretary, and published since 1896.

1897. Publications of the Earthquake Investigation Committee (E. I. C.) of Japan (in foreign languages). Nos. 1–22B (1897–1907). Bulletins 1–4 (1907). This valuable series of publications replaces an earlier series (1892–96) published in the Japanese language, and

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1805. Charles Davison, A Study of Recent Earthquakes. Contemporary Science Series, pp. 355. London, 1905.

1906. F. de Montessus de Ballore, Les Tremblements de Terre, pp. 475. Paris, 1906.

C. The Rossi-Forel Scale of Earthquake Intensity

STRENGTH.

I. Shocks so weak as to be perceived by a single type of seismograph only. Not perceptible on seismographs generally, and confirmed by practiced observers only.

II. Shocks registered by seismographs generally. Confirmed by a small number of persons who are in a condition of rest.

III. Shaking noticed by many persons. Strong enough for the duration and the direction of the shocks to be estimated.

STRENGTH.

IV. Shaking noticed by persons in a state of activity. Shaking of movable objects, such as windows and doors. Cracking sounds in houses.

V. Quaking generally noticed by the entire population. Large objects, like beds and other pieces of furniture, are set in motion. Ringing of some door bells.

VI. General awakening of sleepers, and general ringing of door bells. Swinging of chandeliers, stopping of clocks, visible swaying of trees and bushes. Some persons desert their houses in terror.

VII. Overturning of movable objects, falling of plaster from walls and ceiling, ringing of church bells. General terror; but no damage to structures.

VIII. Throwing down of chimneys, appearance of cracks in the walls of buildings.

IX. Partial or complete destruction of certain buildings.

X. Great catastrophe. Ruined buildings, overturning of earth layers, appearance of clefts in the earth, landslips.

D. The Rudolph Scale of Seaquake Intensity

I. Very slight trembling and generally a sound not unlike that of a rope running out over the rail. Generally perceptible below deck only, and there by those only who are in the more favorable positions. (III of Rossi-Forel Scale.)

II. Slight trembling. Strange unusual shaking in the ship tending to arouse a sleeping crew, and especially perceptible to those who are below deck. (IV of Rossi-Forel Scale.)

III. Trembling in the entire ship, which produces the effect of rolling great casks over the deck. (IV of Rossi-Forel Scale.)

IV. Moderately strong quaking, similar to that which is perceived when the anchor is dropped in deep water

STRENGTH.

and the chain runs out rapidly. (IV of Rossi-Forel Scale.)

V. Rather strong shaking, as though the ship had run upon a coral reef, a sand bank, or a rock, and slipped over it; or had run afoul of another craft or wreck and quickly thereafter had resumed its course. (IV of Rossi-Forel Scale.)

VI. Strong shaking which sets light and loose objects, such as cups, plates, glasses, etc., in motion, making them clink and rattle. The rudder is shaken first one way and then the other, so that the wheel turns in the hands of the helmsman. (V and VI of Rossi-Forel Scale.)

VII. Quite strong shaking and definite shocks, so that the hull gives out a cracking sound, and it is impossible to stand erect upon the deck. (VII of Rossi-Forel Scale.)

VIII. Very strong shaking with definite shocks. Masts, spars, tackle work, and all objects upon the deck are shaken. The compass in the binnacle is thrown down; the thermometer is broken, etc. (VIII of Rossi-Forel Scale.)

IX. Extraordinarily strong shaking with definite shocks. The ship is thrown to one side and is set to rolling. It is raised; loses steerage way, or is arrested in its course. (IX of Rossi-Forel Scale.)

X. Destructive action. People are thrown down upon the deck. Heavy objects are thrown up into the air. Cannons spring from their fastenings. The deck-boards spring up. The ship becomes leaky. (X of Rossi-Forel Scale.)

E. Earthquake Questionnaire Adopted by Prof. G. Gerland, Director of the German Chief Station for Earthquake Study

The following questions are printed upon the back of a postal card and sent throughout the earthquake district requesting a reply to each:

1. Place and date of the earthquake?
2. At what time (hour, minute, and, if possible, second) did it occur? A.M. or P.M.?
3. Where was the observer? In the open air? In the house? In what story?
4. What was the number and duration of the shocks? What was their direction?
5. What were the effects of the earthquake?
6. Earthquake sounds?
7. Behavior of springs, wells, etc.?
8. Other observations?
9. Name and address of the observer?

F. Account of the Great Earthquake in New France on February 5, 1663, from accounts in the "Jesuit Relations"

All students of seismology are placed under obligation to Dr. Reuben G. Thwaites, who has edited in English the voluminous "Jesuit Relations," which have recently been published in seventy-three volumes. In these ancient documents are extremely valuable accounts of the great earthquake in New France which occurred February 5, 1663. Rev. Frederick L. Odenbach, S. J., has extracted from the "Jesuit Relations" the scattered references to this earthquake and published them in the Twelfth Annual Report of the Meteorological Observatory of the College of St. Ignatius at Cleveland, Ohio (1906–7). The following extract is taken with some omissions from Father Odenbach's paper. There are few existing accounts which more clearly and picturesquely set forth the phenomena accompanying a truly great earthquake. The original documents, here given without change, are mainly letters of Jerome Lalemant.

An earthquake, extending over a region more than two hundred leagues in length and one hundred in width—making 20,000 leagues in all—has shaken this whole country, and

caused us to witness some prodigious transformations. Mountains were swallowed up; forests were changed into great lakes; rivers disappeared; rocks were split, and their fragments hurled to the very tops of the tallest trees; thunders rumbled beneath our feet in the womb of the earth, which belched forth flames; doleful and terror-inspiring voices were heard; while whales and porpoises bellowed in the waters; in short, all the elements seemed aroused against us and threatened us with direst disaster. (Letter to Provincial, September 4, 1663.)

On the 5th of February, 1663, toward half-past 5 P.M., a loud roaring was heard at the same time throughout the length and breadth of Canadas. This noise, which gave one the impression that the house was on fire, made all rush out doors to escape so unexpected a conflagration; but instead of smoke and flames, people were much surprised to behold walls tottering, and all the stones in motion, as if they had been detached. Roofs seemed to bend down in one direction, and then back again in the other; bells rang of their own accord; beams, joists, and boards creaked; and the earth leaped up, and made the palisade stakes dance in a way that would have seemed incredible, had we not witnessed it in different places. Then all left their houses, animals took flight, children cried in the streets, and men and women, seized with terror, knew not where to take refuge—expecting every moment to be either overwhelmed under the ruins of the houses, or swallowed up in some abyss that was to open beneath their feet. . Some knelt in the snow and cried for mercy, while others passed the rest of the night in prayer; for the earthquake continued without ceasing, maintaining a certain swaying motion much like that of ships at sea, so that some experienced from this tossing the same heaving of the stomach that one suffers on the water.

This disturbance was much greater in the forests, where there seemed to be a battle between the trees, which crashed against one another, not merely their branches, but even, one would have said, their trunks being torn from their places to

leap one upon another, with the din and confusion that made our savages say that all the woods were drunken.

War seemed to be waged even by the mountains, some of them being uprooted, to be hurled against others, and leaving yawning chasms in the places whence they had sprung. At times, too, they buried the trees, with which they were covered, deep in the ground up to their topmost branches; and at other times they would plant them, branches downward, which would then take the place of the roots, leaving only a forest of upturned trunks.

During this general wreck on land, ice five to six feet in thickness was broken, flying into fragments, and splitting open, in various places, whence issued either great clouds of smoke or jets of mud and sand, which ascended to a lofty height in the air.

Our springs either ceased to flow or gave forth only sulphurous waters. Rivers either disappeared entirely or were thoroughly defiled, the waters of some becoming yellow, and of others red; and our great river St. Lawrence appeared all whitish as far as the neighborhood of Tadoussack (harbor of Saguenay).

Word comes from Montreal that, during the earthquake fence-stakes were plainly seen to jump up and down as if in a dance; of two doors in the same room, one closed itself and the other opened of its own accord; chimneys and housetops bent like tree-branches shaken by the wind; on raising the foot in walking one felt the ground coming up after him and rising in proportion to the height to which he lifted his foot, sometimes giving the sole a quite smart rap; and other similar occurrences of a highly surprising nature are reported from that place.

From Three Rivers they wrote the following account:

"The first and severest of all the shocks began with a rumbling like that of thunder, and the houses were shaken like tree-tops, during a storm, amid a noise that made people think there was a fire crackling in their garrets.

"The first shock continued fully half an hour, although its great violence lasted only a scant quarter of an hour. There was not a person who did not think the earth was about to split open. We further observed that, while the earthquake was almost continuous, still it was not of the same intensity, sometimes resembling the rocking of a great vessel riding at anchor, a motion which caused giddiness in many.

"Sometimes the disturbance was irregular, and precipitated by various sharp movements—sometimes of considerable severity, at other times more moderate; but most commonly consisting of a quivering motion, which was perceptible to one away from the noise and at rest. According to the report of many Frenchmen and savages, who were eye-witnesses far up on our river, the Three Rivers, five or six leagues from here, the banks bordering the stream on each side, and formerly of a prodigious height, were leveled—being removed from their foundations, and uprooted to the water's level. These two mountains, with all their forests, thus overturned into the river, formed there a mighty dike which forced that stream to change and to spread over great plains recently discovered. At the same time, however, it undermined all those displaced lands, and caused their gradual detrition by the waters of the river, which was still so thick and turbid as to change the color of the whole great St. Lawrence River. Judge how much soil it must take to keep its waters flowing constantly full of mire every day for nearly three months."

New lakes are seen where there were none before; certain mountains are seen no more, having been swallowed up; a number of rapids have been leveled; a number of rivers have disappeared; the earth was rent in many places, and it has opened chasms whose depths cannot be sounded; in fine, such confusion has been wrought, of woods overturned and swallowed up, that now we see fields of more than a thousand arpents utterly bare, and as if very recently plowed, where a short time ago were only forests.

We learn from Tadoussacque that the stress of the earth-

quake was not less severe there than elsewhere; that a shower of ashes was seen crossing the stream like a great storm and that, if one were inclined to follow the river bank all the way from Cape Tourmente (half way between Quebec and Saguenay) to that point, he would see some marvelous effects of the earthquake. Near the Bay of St. Paul there was a little mountain, situated on the river bank and a quarter of a league, or nearly that, in circumference, which was swallowed; and as if it had only taken a plunge, it came up again from the depths to be changed into a little island. And farther down near Point Aux Allouettes, a whole forest became detached from the mainland and slid into the river, where it presents to view great trees, straight and verdant, which spring into being in the water overnight.

On the day before the 5th of February the aspect of the sky was quite tranquil and serene, even more so on the 5th until 5 P.M. (at Quebec).

Two circumstances, moreover, render this earthquake very remarkable. The first was its time of duration, it having continued into the month of August, or for more than six months. The shocks, it is true, were not always equally severe. In certain districts, as toward the mountains in our rear (N), the din and the oscillating motion were unintermittent for a long time; in others, as in the region of Tadoussacque, the shocks occurred ordinarily two or three times a day, with great force; and we noticed that in the more elevated places the motion was less than in the level country.

The second circumstance concerns the extent of this earthquake, which we believe to have been general in all of New France; for we learn that it made itself felt from Isle Percée and Gaspée, which are at the mouth of our river, up to Montreal and beyond, as also in New England, Acadia, and other far distant regions. Therefore, knowing as we do that the earthquake extended over a tract of two hundred leagues in length by one hundred in width, we have an area of twenty thousand

leagues which was all shaken at once, on the same day and at the same moment.

There are many things incidental to this earthquake and various circumstances by which we are led to believe that all America was shaken. In fact, we have already ascertained that it extended from the borders of the Iroquois country to Acadia, which is a part of Southern America, that is, a thousand miles. The sault in the St. Lawrence, which on account of its nearness to Three Rivers had received its name from that river, was level. Barbarians most distant of all from us, announce as a fact that they were borne along those recent chasms to the extent of a 30-mile march, nor were they able to find their origin or extent or finally to measure their profound depth.

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